

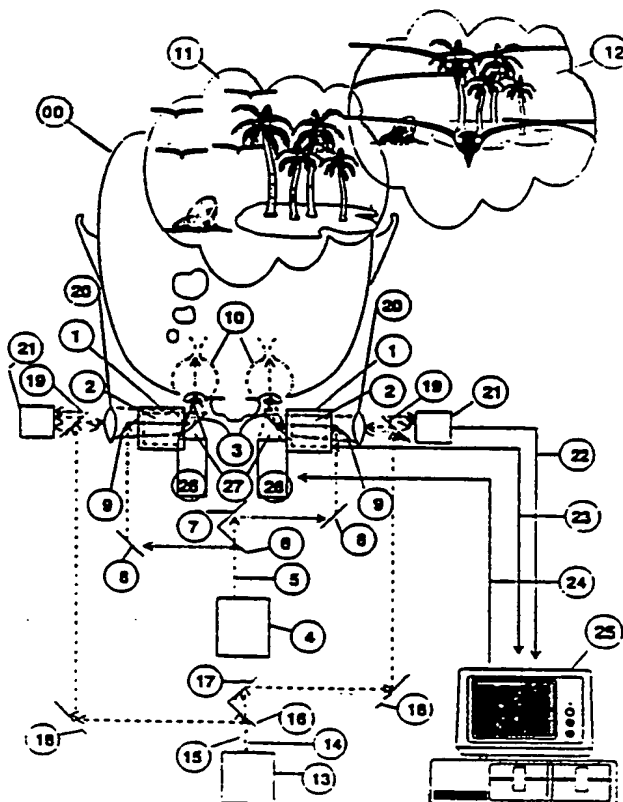


INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁵ : A61B 3/10	A1	(11) International Publication Number: WO 92/01417 (43) International Publication Date: 6 February 1992 (06.02.92)
(21) International Application Number: PCT/US91/04976 (22) International Filing Date: 15 July 1991 (15.07.91) (30) Priority data: Not furnished 19 July 1990 (19.07.90) US (71)(72) Applicant and Inventor: HORWITZ, Larry, S. [US/US]; 6232 Milaga Court, Long Beach, CA 90803-4817 (US). (81) Designated States: AT (European patent), AU (Petty patent), BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), GR (European patent), IT (European patent), JP (Utility model), KP (Inventor's certificate), KR (Utility model), LU (European patent), NL (European patent), + RO, SE (European patent), SU.		Published <i>With international search report.</i>

(54) Title: VISION MEASUREMENT AND CORRECTION**(57) Abstract**

Automated binocular vision measurement and correction measure the refractions of each eye, the topography of the cornea, and the holographic corneal depth. The computer (407) assesses the visual characteristics and performs optical optimization calculations to determine the optimal corneal shapes that would provide the person with precise vision capabilities. An optimal closed pattern trace of low power level laser energy induces the malaxation of the corneal tissue. Laser energy is delivered to a stromal target (806) in the cornea (805) between the epithelium and endothelium. Predetermined parameters are measured using a moire technique. Data representative of an input fringe pattern which includes signal information of the fringe and noise is filtered in a Fourier transform technique to remove noise and back-ground. In conjunction, pattern normalization is used quantifying data from the pattern.



+ DESIGNATIONS OF "SU"

It is not yet known for which States of the former Soviet Union any designation of the Soviet Union has effect.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	ES	Spain	MG	Madagascar
AU	Australia	FI	Finland	ML	Mali
BB	Barbados	FR	France	MN	Mongolia
BE	Belgium	GA	Gabon	MR	Mauritania
BF	Burkina Faso	GB	United Kingdom	MW	Malawi
BG	Bulgaria	GN	Guinea	NL	Netherlands
BJ	Benin	GR	Greece	NO	Norway
BR	Brazil	HU	Hungary	PL	Poland
CA	Canada	IT	Italy	RO	Romania
CF	Central African Republic	JP	Japan	SD	Sudan
CG	Congo	KP	Democratic People's Republic of Korea	SE	Sweden
CH	Switzerland	KR	Republic of Korea	SN	Senegal
CI	Côte d'Ivoire	LI	Liechtenstein	SU⁺	Soviet Union
CM	Cameroon	LK	Sri Lanka	TD	Chad
CS	Czechoslovakia	LU	Luxembourg	TG	Togo
DE	Germany	MC	Monaco	US	United States of America
DK	Denmark				

VISION MEASUREMENT AND CORRECTION

by

Larry S. Horwitz

BACKGROUND

Improving eyesight is vitally important. Precise measurement and correction of physical characteristics of surfaces including features of the eye is thus also vitally important.

Since the Chou Dynasty (circa 479-381 B.C.) man has tried to correct his vision. The measurement of how much correction is required has been a major problem since that time. Typically, in contemporary practice Snellen's charts are used with a phoropter to pragmatically quantify the vision correction. This relies on patient response to quantify the measurement. Auto refractors have been invented that use the knife edge test to quantify the visual acuity via light reflected from the retina. Optical characteristics of the eye are qualified by specific aberrations. Currently, only the first three aberrations of over four hundred are used to correct vision, since this is all that can be measured.

Currently, patient refraction measurements require verbal feedback from the patient in order to quantify the refraction measurement. Thus, in order to perform the measurement on both eyes simultaneously, the number of independent variables in the concurrent indicators allow too many degrees of freedom that there would be no accuracy in the refraction of either eye. Thus, only one eye can be measured at a time.

A characteristic of the eye is needed in order to track its motion. Methods have been used that scar the cornea and track the scar. Tracking the inside edge of the iris is another technique that has been used, however, the iris diameter changes with ambient light and ocular field of regard. Thus, the error induced as the result of iris tracking is larger than the magnitude of the motion measured leaving it an invalid technique.

This invention relates to measuring the and correcting characteristics or parameters of animate and inanimate elements. In particular, the invention is directed to the measurement of surfaces including interfaces of features such as the retinal surface of the eye, the corneal topography and the depth of the cornea. Moreover the invention is directed to measuring both animate and inanimate features whether in a stationary state or in motion.

Different techniques have been developed for the accurate measurement of surface characteristics. Often these techniques rely on a laser beam which impinges on a surface and which is then reflected. A relationship between the impinging beam and the reflecting beam gives information about the surface characteristics. Where the surface characteristics are other than planar, the determination of parameters about the surface can be more difficult to obtain and analyze. Moreover, where the system relies on a physical interferometric technique, characteristics such as the mechanical stability of the system is critical in order to insure accurate measurement. Another feature of importance is the path length to a subject surface to be measured and a path length to a control or reference. Temporal and

spacial coherence are also difficult to stabilize with conventional physical interferometric techniques.

5 A different manner from applying interferometry to measure surface characteristics is that which is obtained from a moire' pattern. The invention is particularly related to moire' patterns.

10 No means exists for accurately determining surface characteristics such as those of the corneal surfaces, e.g., epithelial, Descemet's Membrane and endothelial. Thereby providing keratometric and pachymetric quantified measurements. Moreover, the Applicant is unaware of techniques whereby reflections can be
15 obtained from different surfaces and made to be cooperative such that more specific measurements such as refraction and thickness characteristics of features of the eye can be determined. More specifically, the Applicant is unaware of any known ability to measure and analyze the
20 data from the moire' pattern that are obtained in a manner to apply this data usefully to the object. Such usefulness would include the inherent physical dimensions of a surface, its spacing from another surface, or the degree of movement of the surface or element.

25 Processing fringe interferometric patterns such as moire' patterns to provide measurement characteristics of a surface is valuable. The invention also relates to the processing of fringe patterns generally and specifically, moire' patterns. More specifically, the invention is directed to the processing of fringe patterns containing information concerning characteristics related to the
30 retinal surface, epithelial surface and endothelial surface of the cornea. With such information, valuable

refractive and diffractive characteristics of the eye can be measured.

5 Fringe patterns are caused by an interferometric process. In one form of such process, a collimated light beam is divided so that part of the beam is directed towards a reference and another towards a target. Reflections from the reference and target interfere to provide an interferometric pattern. Interpretation of the pattern can provide measurement characteristics about the target.

15 Another form of interferometric pattern is generated, a moire' interferometric fringe pattern, is by the interference formed when two grating-like transparencies, each with similar but non-identical regular patterns, overlap. The transmission of light through each grating-like transparency creates images. The moire' pattern is the image that is generated through the modulation of the two separated grating transparency images. The measurement of this pattern can provide useful information about measurement characteristics of a surface. This is related to the generation of the light, where that light is generated as a reflection from a surface. The surface can be in the eye, and the pattern is then revealing of eye measurement characteristics.

20 The fringe pattern can be distorted by noise in the system generating the pattern. The noise can be electronically generated, caused by the camera and optical system used in the measurement, or be background or spurious light interference. Additionally, different reflectivity characteristics of the surface unassociated with the measurement being sought can also impact accurate measurement. The reflectivity problems could

5 arise, for instance, where different contrast characteristics of the surface exist. Alternatively, this can be caused by different background sources directed on the surface in a manner unrelated to light associated with the optical measuring system.

The Applicant seeks to provide an improved technique and apparatus for analyzing fringe patterns.

10 This invention also relates to ophthalmic treatment of the cornea so as to improve the overall refractive characteristics of the eye.

15 Different techniques are known for treating the cornea and thereby improving eyesight. In particular, one technique is known as radial keratotomy. This technique is based on radial incisions into the corneal epithelial surface. This changes the shape of the cornea and thereby improves the refractive characteristics of the eye. Radial incisions around the pupil are effected by a laser beam so as to improve the overall refractive characteristics of the eye. Other techniques include orthokeratology which involves the remolding of the cornea by placing a contact lens on the cornea so as to shape the cornea to a prescribed curvature. Other approaches have attempted thermal treatment with radio-frequency coils through a saline bath and the use of a heated wire to perform the shaping.

20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
425
430
435
440
445
450
455
460
465
470
475
480
485
490
495
500
505
510
515
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
605
610
615
620
625
630
635
640
645
650
655
660
665
670
675
680
685
690
695
700
705
710
715
720
725
730
735
740
745
750
755
760
765
770
775
780
785
790
795
800
805
810
815
820
825
830
835
840
845
850
855
860
865
870
875
880
885
890
895
900
905
910
915
920
925
930
935
940
945
950
955
960
965
970
975
980
985
990
995
1000
1005
1010
1015
1020
1025
1030
1035
1040
1045
1050
1055
1060
1065
1070
1075
1080
1085
1090
1095
1100
1105
1110
1115
1120
1125
1130
1135
1140
1145
1150
1155
1160
1165
1170
1175
1180
1185
1190
1195
1200
1205
1210
1215
1220
1225
1230
1235
1240
1245
1250
1255
1260
1265
1270
1275
1280
1285
1290
1295
1300
1305
1310
1315
1320
1325
1330
1335
1340
1345
1350
1355
1360
1365
1370
1375
1380
1385
1390
1395
1400
1405
1410
1415
1420
1425
1430
1435
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
1495
1500
1505
1510
1515
1520
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
1630
1635
1640
1645
1650
1655
1660
1665
1670
1675
1680
1685
1690
1695
1700
1705
1710
1715
1720
1725
1730
1735
1740
1745
1750
1755
1760
1765
1770
1775
1780
1785
1790
1795
1800
1805
1810
1815
1820
1825
1830
1835
1840
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
2110
2115
2120
2125
2130
2135
2140
2145
2150
2155
2160
2165
2170
2175
2180
2185
2190
2195
2200
2205
2210
2215
2220
2225
2230
2235
2240
2245
2250
2255
2260
2265
2270
2275
2280
2285
2290
2295
2300
2305
2310
2315
2320
2325
2330
2335
2340
2345
2350
2355
2360
2365
2370
2375
2380
2385
2390
2395
2400
2405
2410
2415
2420
2425
2430
2435
2440
2445
2450
2455
2460
2465
2470
2475
2480
2485
2490
2495
2500
2505
2510
2515
2520
2525
2530
2535
2540
2545
2550
2555
2560
2565
2570
2575
2580
2585
2590
2595
2600
2605
2610
2615
2620
2625
2630
2635
2640
2645
2650
2655
2660
2665
2670
2675
2680
2685
2690
2695
2700
2705
2710
2715
2720
2725
2730
2735
2740
2745
2750
2755
2760
2765
2770
2775
2780
2785
2790
2795
2800
2805
2810
2815
2820
2825
2830
2835
2840
2845
2850
2855
2860
2865
2870
2875
2880
2885
2890
2895
2900
2905
2910
2915
2920
2925
2930
2935
2940
2945
2950
2955
2960
2965
2970
2975
2980
2985
2990
2995
3000
3005
3010
3015
3020
3025
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
3095
3100
3105
3110
3115
3120
3125
3130
3135
3140
3145
3150
3155
3160
3165
3170
3175
3180
3185
3190
3195
3200
3205
3210
3215
3220
3225
3230
3235
3240
3245
3250
3255
3260
3265
3270
3275
3280
3285
3290
3295
3300
3305
3310
3315
3320
3325
3330
3335
3340
3345
3350
3355
3360
3365
3370
3375
3380
3385
3390
3395
3400
3405
3410
3415
3420
3425
3430
3435
3440
3445
3450
3455
3460
3465
3470
3475
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
3540
3545
3550
3555
3560
3565
3570
3575
3580
3585
3590
3595
3600
3605
3610
3615
3620
3625
3630
3635
3640
3645
3650
3655
3660
3665
3670
3675
3680
3685
3690
3695
3700
3705
3710
3715
3720
3725
3730
3735
3740
3745
3750
3755
3760
3765
3770
3775
3780
3785
3790
3795
3800
3805
3810
3815
3820
3825
3830
3835
3840
3845
3850
3855
3860
3865
3870
3875
3880
3885
3890
3895
3900
3905
3910
3915
3920
3925
3930
3935
3940
3945
3950
3955
3960
3965
3970
3975
3980
3985
3990
3995
4000
4005
4010
4015
4020
4025
4030
4035
4040
4045
4050
4055
4060
4065
4070
4075
4080
4085
4090
4095
4100
4105
4110
4115
4120
4125
4130
4135
4140
4145
4150
4155
4160
4165
4170
4175
4180
4185
4190
4195
4200
4205
4210
4215
4220
4225
4230
4235
4240
4245
4250
4255
4260
4265
4270
4275
4280
4285
4290
4295
4300
4305
4310
4315
4320
4325
4330
4335
4340
4345
4350
4355
4360
4365
4370
4375
4380
4385
4390
4395
4400
4405
4410
4415
4420
4425
4430
4435
4440
4445
4450
4455
4460
4465
4470
4475
4480
4485
4490
4495
4500
4505
4510
4515
4520
4525
4530
4535
4540
4545
4550
4555
4560
4565
4570
4575
4580
4585
4590
4595
4600
4605
4610
4615
4620
4625
4630
4635
4640
4645
4650
4655
4660
4665
4670
4675
4680
4685
4690
4695
4700
4705
4710
4715
4720
4725
4730
4735
4740
4745
4750
4755
4760
4765
4770
4775
4780
4785
4790
4795
4800
4805
4810
4815
4820
4825
4830
4835
4840
4845
4850
4855
4860
4865
4870
4875
4880
4885
4890
4895
4900
4905
4910
4915
4920
4925
4930
4935
4940
4945
4950
4955
4960
4965
4970
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
5030
5035
5040
5045
5050
5055
5060
5065
5070
5075
5080
5085
5090
5095
5100
5105
5110
5115
5120
5125
5130
5135
5140
5145
5150
5155
5160
5165
5170
5175
5180
5185
5190
5195
5200
5205
5210
5215
5220
5225
5230
5235
5240
5245
5250
5255
5260
5265
5270
5275
5280
5285
5290
5295
5300
5305
5310
5315
5320
5325
5330
5335
5340
5345
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
5400
5405
5410
5415
5420
5425
5430
5435
5440
5445
5450
5455
5460
5465
5470
5475
5480
5485
5490
5495
5500
5505
5510
5515
5520
5525
5530
5535
5540
5545
5550
5555
5560
5565
5570
5575
5580
5585
5590
5595
5600
5605
5610
5615
5620
5625
5630
5635
5640
5645
5650
5655
5660
5665
5670
5675
5680
5685
5690
5695
5700
5705
5710
5715
5720
5725
5730
5735
5740
5745
5750
5755
5760
5765
5770
5775
5780
5785
5790
5795
5800
5805
5810
5815
5820
5825
5830
5835
5840
5845
5850
5855
5860
5865
5870
5875
5880
5885
5890
5895
5900
5905
5910
5915
5920
5925
5930
5935
5940
5945
5950
5955
5960
5965
5970
5975
5980
5985
5990
5995
6000
6005
6010
6015
6020
6025
6030
6035
6040
6045
6050
6055
6060
6065
6070
6075
6080
6085
6090
6095
6100
6105
6110
6115
6120
6125
6130
6135
6140
6145
6150
6155
6160
6165
6170
6175
6180
6185
6190
6195
6200
6205
6210
6215
6220
6225
6230
6235
6240
6245
6250
6255
6260
6265
6270
6275
6280
6285
6290
6295
6300
6305
6310
6315
6320
6325
6330
6335
6340
6345
6350
6355
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
6430
6435
6440
6445
6450
6455
6460
6465
6470
6475
6480
6485
6490
6495
6500
6505
6510
6515
6520
6525
6530
6535
6540
6545
6550
6555
6560
6565
6570
6575
6580
6585
6590
6595
6600
6605
6610
6615
6620
6625
6630
6635
6640
6645
6650
6655
6660
6665
6670
6675
6680
6685
6690
6695
6700
6705
6710
6715
6720
6725
6730
6735
6740
6745
6750
6755
6760
6765
6770
6775
6780
6785
6790
6795
6800
6805
6810
6815
6820
6825
6830
6835
6840
6845
6850
6855
6860
6865
6870
6875
6880
6885
6890
6895
6900
6905
6910
6915
6920
6925
6930
6935
6940
6945
6950
6955
6960
6965
6970
6975
6980
6985
6990
6995
7000
7005
7010
7015
7020
7025
7030
7035
7040
7045
7050
7055
7060
7065
7070
7075
7080
7085
7090
7095
7100
7105
7110
7115
7120
7125
7130
7135
7140
7145
7150
7155
7160
7165
7170
7175
7180
7185
7190
7195
7200
7205
7210
7215
7220
7225
7230
7235
7240
7245
7250
7255
7260
7265
7270
7275
7280
7285
7290
7295
7300
7305
7310
7315
7320
7325
7330
7335
7340
7345
7350
7355
7360
7365
7370
7375
7380
7385
7390
7395
7400
7405
7410
7415
7420
7425
7430
7435
7440
7445
7450
7455
7460
7465
7470
7475
7480
7485
7490
7495
7500
7505
7510
7515
7520
7525
7530
7535
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
7605
7610
7615
7620
7625
7630
7635
7640
7645
7650
7655
7660
7665
7670
7675
7680
7685
7690
7695
7700
7705
7710
7715
7720
7725
7730
7735
7740
7745
7750
7755
7760
7765
7770
7775
7780
7785
7790
7795
7800
7805
7810
7815
7820
7825
7830
7835
7840
7845
7850
7855
7860
7865
7870
7875
7880
7885
7890
7895
7900
7905
7910
7915
7920
7925
7930
7935
7940
7945
7950
7955
7960
7965
7970
7975
7980
7985
7990
7995
8000
8005
8010
8015
8020
8025
8030
8035
8040
8045
8050
8055
8060
8065
8070
8075
8080
8085
8090
8095
8100
8105
8110
8115
8120
8125
8130
8135
8140
8145
8150
8155
8160
8165
8170
8175
8180
8185
8190
8195
8200
8205
8210
8215
8220
8225
8230
8235
8240
8245
8250
8255
8260
8265
8270
8275
8280
8285
8290
8295
8300
8305
8310
8315
8320
8325
8330
8335
8340
8345
8350
8355
8360
8365
8370
8375
8380
8385
8390
8395
8400
8405
8410
8415
8420
8425
8430
8435
8440
8445
8450
8455
8460
8465
8470
8475
8480
8485
8490
8495
8500
8505
8510
8515
8520
8525
8530
8535
8540
8545
8550
8555
8560
8565
8570
8575
8580
8585
8590
8595
8600
8605
8610
8615
8620
8625
8630
8635
8640
8645
8650
8655
8660
8665
8670
8675
8680
8685
8690
8695
8700
8705
8710
8715
8720
8725
8730
8735
8740
8745
8750
8755
8760
8765
8770
8775
8780
8785
8790
8795
8800
8805
8810
8815
8820
8825
8830
8835
8840
8845
8850
8855
8860
8865
8870
8875
8880
8885
8890
8895
8900
8905
8910
8915
8920
8925
8930
8935
8940
8945
8950
8955
8960
8965
8970
8975
8980
8985
8990
8995
9000
9005
9010
9015
9020
9025
9030
9035
9040
9045
9050
9055
9060
9065
9070
9075
9080
9085
9090
9095
9100
9105
9110
9115
9120
9125
9130
9135
9140
9145
9150
9155
9160
9165
9170
9175
9180
9185
9190
9195
9200
9205
9210
9215
9220
9225
9230
9235
9240
9245
9250
9255
9260
9265
9270
9275
9280
9285
9290
9295
9300
9305
9310
9315
9320
9325
9330
9335
9340
9345
9350
9355
9360
9365
9370
9375
9380
9385
9390
9395
9400
9405
9410
9415
9420
9425
9430
9435
9440
9445
9450
9455
9460
9465
9470
9475
9480
9485
9490
9495
9500
9505
9510
9515
9520
9525
9530
9535
9540
9545
9550
9555
9560
9565
9570
9575
9580
9585
9590
9595
9600
9605
9610
9615
9620
9625
9630
9635
9640
9645
9650
9655
9660
9665
9670
9675
9680
9685
9690
9695
9700
9705
9710
9715
9720
9725
9730
9735
9740
9745
9750
9755
9760
9765
9770
9775
9780
9785
9790
9795
9800
9805
9810
9815
9820
9825
9830
9835
9840
9845
9850
9855
9860
9865
9870
9875
9880
9885
9890
9895
9900
9905
9910
9915
9920
9925
9930
9935
9940
9945
9950
9955
9960
9965
9970
9975
9980
9985
9990
9995
10000
10005
10010
10015
10020
10025
10030
10035
10040
10045
10050
10055
10060
10065
10070
10075
100

the eye. Additionally, excess energy applied to the cornea can damage the eye through dryness or burning.

5 There is a need to provide a measurement
apparatus, system and method for accurately providing
parameters of selected surfaces such as discrete elements
of the eye. Similarly, there is a need to provide such
information for non-anatomical or inanimate elements such
10 that parameters of the surfaces or elements can be deter-
mined more accurately and their position or movement in
space measured and monitored.

15 Also, there is a need to provide a system for
precisely treating the cornea to effect shaping of the
cornea in a manner to overcome the disadvantages of the
prior art.

SUMMARY

5 This invention provides a system, apparatus,
and method for improved measurement of predetermined
parameters of an element. The element may be animate
such as an eye or an inanimate surface of an element such
as a planar or curvilinear surface or an interface of the
element or its surface with its surroundings. The
10 invention also provides a system for cornea treatment.

15 According to the invention the measurement of a
predetermined parameter of an element comprises the
generation of a collimated light beam and the direction
of that beam onto the element. The beam is reflected
from the element and is directed through a first grating
to develop a synthetic wave front. The synthetic wave-
front is directed through a second grating to develop a
moire' pattern. Analyzing the moire' pattern provides
20 measurement data of the element.

25 In a preferred form of the invention, the
element is an anatomical surface, preferably a surface or
an interface in the eye. Selectively, this is the
retinal surface and the analysis provides refractive data
about the eye. Where the surface is the epithelial
surface the analysis provides topographical data of the
cornea. Where it is the endothelial surface, data on
this provides, together with the epithelial data, a
thickness measurement of the cornea.
0

In a preferred form of the invention, the data
is obtained globally over the corneal surface, corneal
thickness and the retinal surface.

In one preferred form of the invention the data is analyzed to determine movement of anatomical features such as the cornea.

5 In other preferred forms of the invention, collimated beams at selected wavelengths are directed to different surfaces and respective moire' patterns are obtained and analyzed. Preferably, the data for each surface is collectively analyzed. This gives information
10 and overall parameters of the surface and the element defined by the surface.

Also according to the invention, there is provided means for receiving data representative of an
15 input fringe pattern, where the fringe pattern is representative of measurement characteristics. The data includes signal information of the fringe pattern and noise. Filtering means is provided for removing noise so as to provide a signal information representative of the
20 fringe pattern. Thereafter, selectively, the signal information can be scaled to remove further information representative of differences in contrast about the input fringe pattern. This provides scaled signal information representative of a fringe pattern. Demodulation of
25 either the pre-scaled or scaled signal is affected to obtain measurement characteristics represented by the fringe pattern.

In a preferred form of the invention, the
30 measurement characteristic is the retinal surface characteristics of the eye and the topography of the epithelial surface and endothelial surface of the cornea. With this information, refractive and diffractive characteristics of the eye are obtained. This can permit for correction
35 by prosthetic devices such as eyeglasses or contact

lenses or by treatment of the eye with laser-directed power.

5 In a further preferred form of the invention, the fringe pattern is caused by a moire pattern. The filtering means is preferably a Fourier transform. The filter effectively scans the input to determine the central frequency and estimates the spectral content of the signal. The input power across the spectrum is then
10 estimated. After the estimations are obtained, this is treated by a filter transfer function computation. Complex multiplying the transform of the input fringe signal with the transfer function, and then inverse transforming the multiplied output provides an output
15 fringe image without noise.

20 In yet a further preferred form of the invention scaling of the signal is affected to eliminate the effects of different reflectivity about the surface.

25 Also by this invention, treatment of the cornea is achieved to effect corneal reshaping in a manner to improve the refractive characteristics of the eye. Laser energy is delivered to a target in the cornea to effect heat treatment of the cornea. There is means for generating the energy in a laser beam and for focusing this energy to a selected part in the cornea at a prescribed depth between the epithelial and endothelial surfaces. The energy is adapted to heat a target area and the laser
30 beam traces a selected target path in the cornea. Heating the corneal matter along the path thereby changes the shape of the cornea.

35 In a preferred form of the invention, the traced path is a closed loop in the form of a Schwalbe's-

like line. The effective "Schwalbe's line" may be a regular curve or an irregular shape.

5 Preferably, the heated area is the stromal region in the cornea, and the laser energy is obtained from a carbon dioxide laser focused to avoid heating of the epithelial and endothelial surfaces.

10 In a preferred form of the invention, the laser is inter-operative with means for measuring the refractive characteristics of the eye, the corneal shape and corneal depth. As the thermal treatment is imparted to the cornea, a feedback is achieved such that the optimal refractive conditions are obtained.

15 In some cases, both eyes can be treated substantially simultaneously while a patient views a 3-D image through a stereoscope.

20 The moire technique used in this invention allows for adjustable sensitivity of measurement and insensitivity to motion of the eye to allow high quality, quantified ocular aberrations to be measured without patient response. Near infrared energy of the Nd:YAG
25 laser of wavelength, 1.06 micrometers, has a high reflection coefficient in the choriocapillaris and pigmented epithelium of the retina. If the laser beam is well collimated when it enters the eye, the reflected wave front can be analyzed to measure many, and up to
30 about two hundred fifty six aberrations of the eye.

Other features of the invention are now further described with reference to the accompanying drawings and detailed description.

11

DRAWINGS

In the appended drawings like numbers denote like parts.

FIG. 1 shows the system in accordance with the present invention for closed loop automated low energy refractive tissue-therapy for the binocular refractive correction in animals including humans, as depicted here, spectral biometers for the initial measurement of ocular optical characteristics as well as real-time feed back during the automated procedure are present for both eyes as well as the laser sources;

FIG. 2 the invention takes advantage of the spectral reflectance characteristics of the ocular surfaces in the spectral-biometers;

FIG. 3 shows the light path in a spectral-refractor;

FIG. 4 indicates the moire-technique for sensing of the wave front reflected from the respective ocular surfaces of interest in the invention;

FIG. 5 shows the keratopographer beam interface with the anterior epithelial surface of the cornea;

FIG. 6 illustrates the light path of the keratopographer beam as it samples the entire epithelial surface of the cornea in a continuum;

FIG. 7 indicates the reflective interaction of the light used in the pachytopographer to measure the entire surface of the Descemet's membrane or endothelium,

this surface is related to the epithelial surface to provide the pachymetry;

FIG. 8 shows the optical path of the pachytographer laser beam;

FIG. 9 is the flow of the algorithm that processes each of the moire patterns as they occur from the light reflections from each of the ocular surfaces of interest in this invention and the ocular characteristics that they provide;

FIG. 10 shows the noise and background filtering technique as used in FIG. 9;

FIG. 11 shows the technique by which the moire patterns are processed in order to normalize the contrast over each entire pattern, this is the final step in processing the pattern before the wave front data is extracted from them;

FIG. 12 indicates the "trackability" of the moire pattern from the eye (these patterns have not been processed as described in FIGURE's 10 and 11) providing an ideal eye tracking system;

FIG. 13 illustrates the low energy delivery optics to the later half of the stroma, this is an f/0.76 beam incident onto the cornea;

FIG. 14 is the power budget when a carbon dioxide laser beam is used in the corneal tissue therapy for refractive correction, this delivery system is not restricted to this laser;

FIG. 15 are the trace patterns for typical vision aberration, i.e. myopia, hyperopia and astigmatism; and

5

FIG. 16 is the closed loop algorithm for the automatic vision correction system with automatic feed back.

DESCRIPTIONIntroduction and Overview

5 There is provided a system for automatic closed loop binocular vision correction.

10 The refractions of both eyes of the patient are measured simultaneously as a three dimensional perception video is viewed. The predominant action changes from the near field of view to the far field in a contiguous manner in combination with dark to bright fields. Con- currently, the shape and thickness of the cornea are measured continuously throughout the entire extent of the
15 cornea. These measurements are made at the frame rate of the video camera in the system, e.g., 60 measurements per second. Anomalies are disregarded. The field distances and dark shades are temporally correlated with the depth of field (i.e., near sighted or far sighted) under going
20 investigation.

 After a period of measurement (less than a minute) the data is manipulated and the complete optical characteristics of both eyes are known. The optical
25 aberrations of the eyes are quantified in Zernike polynomials measuring 256 aberrations simultaneously (as opposed to the 3 aberrations measured in contemporary refractions). Since the polynomials are orthogonal, the aberrations are separable and can be treated as such. An
30 optimization optical analysis is performed that treats the cornea as the deformable element. Simultaneous far field and near field optimization are performed in order to optimize the optical capability in both fields and all intermediate points. Constraints are put on the corneal
35 manipulation in both magnitude and direction of local

displacement and spatial frequency content of the variation. The cornea are then modeled in finite element representations for both structural analysis and heat transport analysis as reported by J. A. Scott in "A
5 finite element model of heat transport in the human eye", Phys. Med. Biol., Vol. 33, No. 2, 227-241 (1988).

These models are then used to determine where
10 to heat the stromal region in order to generate the corneal shape determined. The constraints put on this analysis are that the thermal energy must be applied to the later half of the corneal depth, the trace pattern is to be a closed loop and the temperature rise in the
15 cornea is not to be more than 10° C. The closest fit to the corneal shapes is determined. If the precise shapes are not achievable, optical analyses are performed on the best fit corneal shapes to determine if the figure of merit is within our specifications. If satisfied we go to the next step; if not the two analyses are optimized.
20 This optimization is performed by eliminating the highest order aberrations from the correction. Thus, potentially only 60 aberrations will be corrected. Trace patterns and dwell times along the pattern are now defined for each eye.

25 Laser gimbaling systems directs the laser energy along the prescribed patterns. Through all of this time (roughly, 10 seconds) the eye motion sensor keeps track of the eye motions. If the eyes move, the
30 biometers can still provide the measurements. If the eyes move during the laser tracing procedure, the data is fed into the gimbaling system to provide the compensation. In the case of a radical movement the therapeutic laser system would turn off; then resume again as soon as
35 the tracking of the eyes is re-initiated. As the corneal

malaxation is induced if the expected bending does not occur, new control laws are developed at each location so that in real time the dwell time of the laser energy is adjusted. As the thermal trace is completed the refractions of the eyes are again measured. If within the limits allowed, the procedure is recorded and stored in the patient file. If on the other hand the refraction measurement falls outside the required limits, the procedure is re-initiated. If after several iterations the limits cannot be met the system indicates the maximum correction achieved and records the results in the patients files.

The biometers measure the optical wave fronts reflected from the two corneal surfaces and the retina. Spectral reflectance characteristics of these surfaces allow the segregation of the wave fronts so that all optical characterizations can be measured simultaneously. The spectral reflection peaks are as follows:

Corneal epithelial surface	470 nanometers
Corneal endothelial surface	525 nanometers
Retinal surface	1060 nanometers.

The 1060 nanometer beam is collimated and directed into the eye. It is focused by the corneal media and the lens, reflected from the retina and then exits the eye by the same path. Wave front analysis is performed by passing the light through two Ronchi gratings that are arranged parallel in planes normal to the direction of propagation and rotated with respect to each other in those planes. The resulting moire pattern is imaged on a mat screen and then recorded by a video camera. The recorded image is processed via Fourier transform techniques and the image contrast is normalized

throughout the pattern. Closed form equations are then applied point by point (i.e., pixel by pixel) to derive the shape of the wave front. With the spatial characteristics known, the wave front is then fit to 256 orthogonal Zernike polynomials. Each of the coefficients of the polynomials is then reduced by a factor of one half to compensate for the double pass characteristic of the measurement. Now the optical aberrations of the eye are defined precisely.

An argon ion 470 nanometer laser beam (or any other laser emitting in the 470 nm spectral region) is collimated then passed through an $f/1.25$ converging lens and directed toward the center of curvature of the cornea. This light is partially reflected from the surface of the cornea. The reflected light is collected by the $f/1.25$ lens and directed toward the same Ronchi gratings. The resulting moire pattern is spectrally separated from the refractor pattern and processed in the same manner. Since the reflection is from a single surface the double pass effect does not occur and the polynomial coefficients are not divided by 2. This data is the precise topographical description of the corneal surface. This is the keratopographer system.

Since the moire pattern moves with the eye and the pattern uniquely defines the surface of the eye, the pattern can be tracked to qualify and quantify the motion of the eye. Simple eye motion can be characterized by tracking the transverse plane and area tracking in the axial direction. Detailed eye motion tracking is achieved by this technique integrated with the actual analysis of the moire pattern. This eye dynamics sensor is used to track the motions of the eyes during this entire procedure. The subsystem of the invention can be

used in Heads-Up-Display (HUD) system for fine pointing and tracking mechanisms; mental alertness indicator that is characterized by eye motion (sporadic or intentioned) used to detect falling asleep, drug usage or alcohol usage; video games where eye motion is an interaction with the game; and in research where eye motion is a parameter.

The final biometer is the pachytopographer that measures the corneal depth continuously throughout the corneal region. The same argon ion laser (or any other laser producing light in the 525 nanometer spectral region) also produces a 525 nm beam. By directing the beam through the same optical ($f/1.25$) path, as the keratopographer, a portion of the light is reflected from the endothelial surface or Descemet's membrane of the cornea and is provided the same wave front sensing after spectral separation from the other two beams. This data is the topography of the endothelial surface. By correlating the endothelial and epithelial topography and subtracting the pachymetry of the cornea is provided.

The low energy refractive tissue-therapy system makes use of the thermal effects of light. Photometric power itself does not cause therapeutic heat. Power density causes the heating that induces the malaxation of the corneal stroma tissue, the lamella. The power densities at the anterior epithelium and in the later half of the stroma can be chosen by appropriately selecting the convergence rate, or f -number, of the beam, the power in the beam and the wavelength of the beam that lies within any spectral absorption band of the water around the stromal lamella.

5 In this invention, the predominant absorption
band of water (H_2O) is used. The intent is to heat the
lamella via convection rather than the application of
photometric energy directly to the tissue (energy applied
to human tissue may have negative long term effects,
e.g., cancer or mutated tissue). However, this optical
configuration can be applied to any optical delivery
system used in thermokeratoplasty (TKP) or photo-
thermokeratoplasty. There are other absorption lines 2.6
10 micrometers, 3.9 micrometers and 6.05 micrometers
according to M. A. Mainster in "Ophthalmic applications
of infrared lasers-thermal considerations", Invest.
Ophthalmol. Visual Sci., Vol 18, No. 4, 414-420, (1979).
Lasers operating in these regions are also useful for
15 this application. There are two absorption bands, at 1.3
and 3.4 micrometers, which are strictly for the lamella.
Though use of this wavelength is not recommended in this
invention applications of lasers of these wavelengths
will also make use of the optical delivery system in this
20 invention for the most effective TKP application.

25 The therapy beam is pointed to the later half
of the stroma with a f/0.76 beam. The pachytograph and
keratograph data are used to correctly position
the beam to the 0.25 millimeter accuracy. Using a carbon
dioxide laser the power incident on the eye is 0.2 watts
with an intensity of less than 5 milliwatts per square
centimeter, which when partially absorbed in the stroma
causes no malaxation of the lamella. The focus of the
beam, and the region where the intensity is high enough
to induce the lamella malaxation, is a spherical volume
25 microns in diameter. Less than a microwatt arrives at
the Descemet's membrane and endothelial surface of the
cornea. The laser is gimballed by x,y,z linear motor

drives under the control of the computer algorithm that derived the trace and using the data from the biometers.

Detailed Description

5
10
15
20
FIG. 1 schematically shows an embodiment of the invention. This figure can be split into two monocular systems thereby proceeding with one eye at a time. The subject 00 looks into the system and view two displays 1 simultaneously, i.e., one with each eye 10. The displays are viewed via the reflections from the two beam splitters 3 and 2. A three-dimensional dynamically moving scene is provided the subject since each of the displays is playing a video of separate cameras having the perspective of each eye. An example of this is illustrated in 11 and 12 with the birds flying from far away toward the subject. The subject is told to watch the moving objects in the scene thus he is adjusting his focusing field over a wide range. As the depth of field is changing, the target brightness and contrast is changing. All of these parameters are temporarily correlated to the biometers to accurately calibrate the refraction measurements being made.

25
30
35
In FIG.2 the spectral reflectance characteristics of the eye 101 are illustrated. Assume a wide spectral band white light source 102 illuminating the eye. A predominant spectral region of the light will be reflected from each surface of the eye. The cornea 103 has two surfaces of interest and the retina 108 provides the reflection for the optical system sampling wave front. Though there is specular reflection at each surface there is a spectral response embedded in each reflection. Thus, at each surface there is a different "color" reflected. Spectral reflection 104 from the

anterior epithelial corneal surface is nominally 470 nanometers. Descemet's membrane and the endothelial are at the back surface of the cornea. Peak spectral specular reflectance 105 occurs at 525 nanometers. The lens 106 has two surfaces which can reflect energy 107 in the yellow spectral region. Finally, the retina 108 reflects 109 very strongly in the 1060 nanometer region.

The Neodymium:YAG, diode or other laser producing energy in the 1060 nm spectrum and collimator 4 in FIG. 1 provides the collimated beam 5 (dash-dot line) that is equally divided into two paths toward each eye at the beam splitter 6 then directed into the right and left eyes via fold mirrors 7 and 8, beam splitter 9 and beam combiner 3. The collimated beams pass through the optics of the eyes (or, single eye in the case of a monocular system), reflect from the retina and pass back through the eye optics and is directed back to the moire wave front analyzer 21.

This optical path is shown in FIG. 3. The collimated beam 301 reflects from the aperture sharing element 302 and is directed into the eye passing through the cornea 303, the lens 304 and on to the retina 306. It then is reflected out of the eye and this time passes through the aperture sharing element 302 on its way 307 to the wave front sensor.

The wave front sensor is schematically illustrated in FIG. 4. The wave front to be measured 401 enters the sensor and passes through two gratings 402 and 403. The gratings are in parallel planes that are rotated an angle θ with respect to each other and axially displace a distance d . The resulting moire pattern 404 is visible on the matte screen 405 and imaged by the

camera 406. If the incoming wave front is as referenced and unperturbed A (dotted line) will result in a moire pattern as illustrated by pattern A. When there is aberration in the wave front as in B (solid line), an example of the moire pattern is given in B. The computer 407 then analyzes the wave front.

In FIG. 1, the path of the 1060 nm beam to the computer image via 22 then the analyzed beam provides the objective refraction measurement of the eyes, 25. The analyzed wave front is temporally coordinated with the focus require by the video programming, as indicated by 23, to assess the entire field and contrast acuity and accommodation.

In order to provide keratopographical measurements of the cornea of eye 10 a coherent light source producing radiation in the 470 nanometer region is required. In FIG. 1 13 is that radiation source. Light beam 14 (dashed line), the collimated coherent beam from 13, is divided into two beams at beam splitter 16 and directed toward each eye via fold mirrors 17 (left eye only), 18, beam splitters 19, through the nulling lenses 20 and beam combiners 3. Light reflected from corneal epithelial surfaces is directed back through nulling lens 20, through beam splitters 19 into the moire' wave front analyzer.

In FIG. 5 the collimated beam 501 (14, FIG. 1) is focused by nulling lens 502 (20, FIG. 1) such that the converging light 506 is focused near the center of the radius of curvature of the cornea 503, r (505), of the eye 504. Light specularly reflect form the corneal surface will be referenced to the focus of 502 as the

reflected light 501 (left hand pointing arrows) is directed toward the wave front analyzer.

5 Three colors will be incident onto the wave front analyzer. In order to analyze each wave front spectral filters are used on the camera focal plane of separate from the camera, in which case three cameras will be required in 21, FIG. 1.

10 Keratometric measurements are made with the optical system in FIG. 6. Collimated 470 nanometer light 602 (14, FIG.1) is partially reflected from beam splitter 603 (19, FIG.1) and directed onto the eye as previously described. Reflected light partially passes through the
15 beam splitter 603 and 606 toward the wave front analyzer.

20 Pachytopographical data is measured by measuring topographical data from the Descemet's membrane and/or endothelial surface. Data is correlated with the keratopographical data to obtain the pachytopographical data.

25 In FIG. 1 525 nanometer spectral band light 15 (dotted line) is obtained from 13. An Argon Ion laser can be used as the source of both 14 and 15. Light 15 is divided toward each eye via the same optical path as 14. Upon reflection from the endothelial surface and/or Descemet's membrane 15 traces the same optical path
30 (except for wave front variations due to the respective reflection surfaces) to the wave front analyzer.

35 In FIG. 7 the path of the 525 nm band light, pachytopographer beam, indicates the input beam 701 (15, FIG. 1) is focused by the nulling lens 702 (20, FIG. 1) toward the center of curvature of the cornea 705 (505,

FIG. 5). Light 701 passes through epithelial surface 703 specularly reflects from the endothelial surface and/or Descemet's membrane 707. Reflected wave front 701 (left hand going arrows) are referenced to the focused wave front of 702.

Optical system of pachytopographer is schematically shown in FIG. 8. Measurement beam 801 (701, FIG. 7) is partially reflected from beam splitter 802 (19, FIG. 1) toward eye, as described in FIG. 7. Specularly reflected light partially passes through 802 with the output wave front 807 directed toward the wave front analyzer.

Methodology for analyzing moire' patterns to describe the ocular parameter of interest is schematically shown in FIG. 9. After the patterns at the three different wavelengths are spectrally segregated, patterns are filtered with respect to noise and spurious background. It is necessary to normalize the pattern contrast that is a result of surface reflectance and transmission inhomogeneity. Patterns are then reduced to analytic wave fronts, Oster, et al., in "Moire' Patterns", Scientific American, May 1963, pp. 54-63. With respect to the pattern analyzed, the surface or wave front of concern is provided. Keratometry data is correlated with Descemet's membrane and/or endothelial surface data to provide the pachymetry data.

In FIG. 9, the input moire' pattern 908 is directed to block 909 which is the filter to remove noise and background. The moire' pattern 908 can be shown with fuzzy light and dark regions. After filtering in block 909, the pattern becomes discrete and separate dark and light lines as indicated in block 910. As can be seen,

the dark lines have different degrees of darkness which is caused by different surface reflectivity and/or transmission characteristics with respect to the element being measured. The signal is represented by block 910, is directed then to the means for removing information representative of differences in contrast about the fringe pattern as indicated by block 911. This effects scaling of the fringe pattern to provide a signal as indicated in block 912 which represents dark lines of equal intensity. The output signal 912 is directed to means for demodulating the scaled signal information of the fringe pattern to obtain measurement characteristics represented by the fringe pattern, such demodulating means being generally indicated by block 913. From block 913, the different characteristics of refraction, epithelial surface, and endothelial surface measurements can variously be obtained as diagrammatically illustrated through arrows 914, 915 and 916, respectively. The information can then be further processed appropriately. The refraction information can give aberration analysis. The epithelial surface information can give keratometry data, and the information about the endothelial surface and endothelial as indicated collectively by arrows 917 and 918 can be used to give pachymetry data. The representations of the demodulated signal information can be received multiple time over a short temporal period. Anomalies are eliminated and there are means to average the multiple representations to obtain an appropriate output signal 914, 915 and 916 representative of the measurement characteristics.

The methodology of filtering to eliminate noise and background from the respective pattern is shown in FIG. 10. Local areas of the pattern are chosen with respect to the spatial variation of the noise and

background. With respect to each local area a guard band is chosen encompassing it in order to transform the data to the spatial frequency domain using a Fourier transform. The fundamental frequency of the domain is that provided by the configuration of the moire' wave front analyzer. A noise and background power spectrum data is then estimated and combined with the signal estimation to provide the complex transfer function H . Spatial frequency data of the noise/background free pattern, P , is defined by the complex product of the input pattern power spectrum and the transfer function. An inverse Fourier transform of P is the output moire' local area pattern. Local area patterns are then moved throughout total pattern in order to effect the entire moire' pattern.

In FIG. 10, the input moire' local area pattern 1000 is directed into a block 1001 for effecting a Fourier transform of the input and pre-processed moire' pattern. The pattern in the spatial frequency domain is represented by $M(jw_x, jw_y)$. The output from the Fourier transform is indicated as a signal. The signal is directed to means 1002 for estimating the signal spectral content as indicated by $f_0 = p/(2\sin \theta)$. The output from block 1002 provides a signal as indicated by $S^*(jw_x, jw_y)$.

Secondly, there are means 1003 for estimating the input power spectrum and the representation on spatial domain component is indicated by $|M^*(jw_x, jw_y)|^2$. Both these estimations are directed as indicated by arrows 1004 and 1005 to a filter transfer functions block 1006 where a computation is effected to provide an outlet signal represented as:

$$H(jw_x, jw_y) = \frac{|S^*(jw_x, jw_y)|^2}{|M^*(jw_x, jw_y)|^2}$$

27

Normalized pattern contrast is achieved via the methodology describe in FIG. 11. Spatial intensity characteristics of the pattern are determined. A window dimension is then determined. Window is then moved throughout the pattern in which a maximum and minimum intensity at each location is determined. The pixel value $p(x,y)$ is then adjusted to the normalized value $p'(x,y)$:

$$p'(x,y) = \frac{p(x,y) - p(\min)}{p(\max) - p(\min)}$$

for all (x,y) within each window (block 1120).

The noise free moire' pattern image 1111 is directed along line 1112 to a circuit 1113 to determine the centroid and variance of all the pattern $p(x,y)$. The output data 1114 is directed to block 1115 where the local area window size is determined in order to locally adjust for contrast inhomogeneity. Window 1116 is then moved throughout the entire pattern 1117 locally determining the maximum, $p(\max)$, and minimum, $p(\min)$, pixel values (intensity) within the window 1118. This data is then passed 1119 to the normalizing equation for every point (x,y) within the window 1120. Output pattern is now normalized in contrast (as indicated in FIG. 9, 912).

Effectively, the compensation means includes means for dividing the fringe pattern $p(x,y)$ into discrete pixels and means for defining a neighborhood about each pixel and means for collecting data within that neighborhood, the neighborhood being that data within the window. There are also means for computing the minimum and maximum contrast signal as

indicated by block 1118 within the neighborhood or window and then the means is scaled to produce a scaled value of the pixel within the neighborhood as indicated in block 1120.

This signal is suited for wave front analysis and pattern tracking.

Moire' patterns derived from the corneal epithelial surfaces provide a characteristic by which the eye can be tracked as shown in FIG. 12. In plane tracking of the centroid of the pattern provide coarse tracking of eye to within 1.41 pixels. Analysis of the patterns provides the fine tracking algorithm. Area tracking of the pattern provides axial translation with pattern analysis again providing fine tracking data.

In FIG. 12, the illustration indicates the manner in which tracking can be effected. This is illustrated relative to the axis as depicted in the x,y,z coordinate system as illustrated in the axis diagram to show three dimensional representations 1200. The point of juncture between the x,y,z axis is the 0 indicator. The moire' pattern as indicated in the x,y plane 1210 shows the effect of the relative movement when at the intersection 0 the pattern 1201 is represented. Movement to the left is indicated pattern 1202 and movement to the right along the wire plane is indicated by pattern 1203. Movement along the z axis 1211 into and away from the x-y plane 1210 is indicated such that movement away from the x,y plane is indicated by pattern 1204, movement at the intersection by the 0 position, and movement from the intersection out of the paper by pattern 1205.

Compound movement being a combination of movement in the x,y and z planes as indicated by arrow 1212 causes a representation 1207. Further movement is indicated by arrow 1213 which gives you a representation 1206. Movement as indicated by arrow 1214 gives you a representation 1208 and further movement is indicated by arrow 1215 which gives you a representation 1209.

In application to the refractive tissue therapy system, the location is fed back to the computation system on 22 FIG. 1 and the laser gimbaling 24 FIG. 1.

A mechanism of delivery of low energy refractive tissue therapy is shown in FIG. 13 (26 FIG. 1). The input beam 1301 (27 FIG.1) is focused by a f/0.76 (or similar) lens 1302 to the later half of the corneal 1305 stromal region 1306 to a spot 1307 20 to 50 micrometers in diameter (assume a spherical volume). Therapy beam is focused such as to not deliver the energy density to the corneal epithelial surface 1303 or the endothelial surface 1309 that will induce enough thermal energy to cause malaxation of the tissue. Malaxation is only induced in volume 1307. Gimbaling (x,y,z) of the therapy beam is performed for local treatment throughout the entire cornea, as discussed later. In the case of a carbon dioxide (CO₂) laser the power budget of the therapy beam is shown in FIG. 14. Though 0.2 watts is incident upon the eye, power density is low enough that malaxation will not occur. At the focus around the 20 to 50 micrometer diameter volume the power density is high enough to induce the 10° C elevation of temperature. At the endothelial surface the intensity will not cause endothelial cell damage.

Typical and representative trace patterns of the therapy beam is illustrated in FIG. 15. It is evident that the patterns form a pseudo Schwalbe's line. Schwalbe's line holds the cornea erect in the spherical form. By forming a closed loop trace pattern 1502 a, b & c the corneal malaxation has shown to provide a steady state form of the cornea post-malaxation. As representative, trace 1502a will provide a correction of myopic sight impairment. Likewise 1502b hyperopic correction and 1502c is a correction for this arbitrary astigmatism.

The invention performs the high order corrections utilizing a thermal corneal tissue therapy technique in conjunction with optical and corneal structural analysis.

In FIG. 16, the automated system is illustrated in a closed loop. With incoming data providing the refraction impairment, keratometry and pachymetry from the biometers (1601, 1602 and 1606, i.e., 22 and 23 in FIG. 1), optimization for the corrected ocular optical system is determined by least squares fitting the measurements (who are themselves locally discriminated and averaged) to a discrete number of Zernike polynomials in the optical optimization processor 1615 (in computer 25 FIG. 1). Desired corneal shape is derived (given spatial constraints), or contact lenses or spectacles are defined (1618). In the case of corneal therapy, a finite element model of the cornea is developed from the keratometry and pachymetry data in block 1616. Thermal therapy is then defined by the thermal analysis in block 1617 as to locations of the therapy, i.e., laser beam trace, and dwell times of the beam at each site (1621 and 24 in FIG. 1). For medical acceptability the data is displayed in block 1619. Spatial coordinates of the beam are the

31

5 given 1620 to the gimbaling system 1615 to trace the closed loop trace. As well, locations of the eyes are provided via the keratopographers 1602 and the tracking algorithm 1614 in real-time on line 1613 into the loca-
10 tion file 1614 for the thermal therapy gimbaling system. Upon gimbaling completion the optical characteristics of the eyes are again measured 1601 and 1602. If criteria are passed for the optimal patient visual correction in block 1603, the data is passed 1604 to block 1605 where it is recorded and the procedure is complete. On the other hand if the criteria is not passed, the new data is passed back through the system, i.e., to blocks 1609 and 1608 (the current pachymetry is again measured 1606 and provided to block 1607) to initiate a new iteration of
15 the corrective procedure. Thus, closing the vision correction control loop.

20 The system as indicated operates in a closed loop to effect optical measurements and also to determine the degree of corrective treatment that is necessary for the optical element. When the optical treatment is effected, the closed loop can provide different refrac-
25 tive signals and this can be adapted so that ultimately the optical conditions are rectified.

The invented spectral-refractor system requires no patient conscious feed-back. Thus, a binocular refraction can be performed. The corneal topography and the corneal holographic depth measurement require no
30 patient feedback. Therefore, all of the parameters of the patient's visual characteristics can be measured simultaneously in a binocular mode.

35 Corneal global topography is a mechanism needed to sample (i.e., make measurements from) the entire

surface of the cornea. By combining ocular spectral reflectance information with wave front sensing technology, the corneal surface topography is precisely and continuously measured. Such measurements will provide precise biometrics in order to fit contact lenses and to analyze the cornea for refractive surgical or therapeutic procedures.

The technique used in the keratometric method permits the dynamics of the eye to be tracked, i.e., an eye tracking sensor. This can qualify eye motion or quantify it to 200 microradians (or, 0.01 degree).

This technique is useful in ophthalmic surgery, refractive surgical and therapeutic procedures, pointing and tracking in helmet mounted systems, sensors to determine if a person is falling asleep (e.g., automobile sleep alarms), mental acuity tests (e.g., alcohol and drug tests), and video games in which eye tracking would be used as the interaction with the game.

Laser energy with the appropriate spectral absorption characteristic of the stromal region in coordination with the optical delivery system produces the therapeutic effect needed to induce refractive alteration. Corneal stromal region temperature must be elevated by 10° C in order to produce the malaxation as can be derived from E. L. Shaw and A. R. Gasset in "Thermokeratoplasty (TKP) Temperature Profile", J. Invest. Ophthalmol. 13, No. 3, 181-186 (1974), and J. A. Scott in "The computation of temperature rises in the human eye induced by infrared radiation", Phys. Med. Biol., Vol. 33, No. 2, 243-257 (1988). Temperature rise is controlled by the dwell time of the focus of the laser beam. Corneal shape change is controlled by the trace pattern

of the gimballed laser beam. This is a low energy refractive tissue technique. An automated, closed loop control refractive correction system, integrates this with the spectral refractor, the keratopographer, the pachytograph, and the eye dynamics sensor.

Software performs optical analysis of the eye, and structural and thermal analysis of the cornea. This is a closed loop, ophthalmic system. No conscious patient feedback is required for the system to perform. Thus, the system can be used for any mammals, e.g., veterinary, mentally retarded patients, patients who are too young to communicate or are otherwise unable to communicate.

The invention seeks to perform closed loop refractive correction to both eyes of the subject patient simultaneously and automatically. No subjective feedback from the patient will be required by the system. While viewing a three dimensional dynamic video scene, the patients ocular parameters will be measured, calculation performed and thermal refractive tissue therapy performed. The system is closed loop in the sense that if the procedure does not produce the desired refractive and corneal effects desired, it compensates for the errors automatically.

Automatic, binocular or monocular refractive measurements of the vision of subject patients without causing eye strain or requiring verbal response should be possible. Contact lens or spectacle lens prescriptions will likely be provided automatically as well as prescribed refractive surgical or tissue therapeutical procedures.

Precise topographies of corneal surface to be used in contact lens fitting, analysis of corneal scarring and lesions, ophthalmic research, and refractive surgical and tissue therapeutical procedures should be possible.

5

Holographic topographies of the corneal depth may be used in ophthalmic research, refractive surgical and tissue therapeutical procedures, and corneal diagnostic analysis.

10

Quality control of inanimate elements such as objects where the surface of the product is an indicator of the product quality is possible. Examples are ball bearings or golf balls where the sphericity is important, optical components where surface quality is important, injection molded elements where surface quality is important, and cut gem quality where the relative position of cut faces are important.

15

20

Many more examples and applications of the invention exist, each differing from the other in matters of detail only. The invention is to be considered limited only by the following claims.

CLAIMS:

1. Apparatus for measuring a predetermined parameter of an element comprising:

- (a) means for generating a collimated light beam;
- (b) means for directing the beam onto the element wherein the beam is reflected from the element;
- (c) means for directing the reflected beam through a first grating to develop a wave front;
- (d) means for directing the wave front through a second grating to develop a moire' pattern; and
- (e) means for analyzing the moire' pattern to produce measurement data of the element.

2. Apparatus as claimed in claim 1 including a nulling converging lens between the element and the first grating, the nulling lens having related to the surface of the element to provide a beam front substantially parallel to the surface of the element.

3. Apparatus as claimed in claim 1 wherein the analyzing means includes computation means for removal of noise and for determining a substantially noise-free moire pattern thereby to provide measurement data of the element.

4. Apparatus as claimed in claim 1 including means for selecting a collimated beam of a predetermined wavelength suitable for reflection from a selected element.

5. Apparatus as claimed in claim 4 wherein the beam has a wavelength in the range of about 400 to about 1100 nanometers.

5 6. Apparatus as claimed in claim 5 wherein the wavelength is about 1060 nanometers and wherein the beam is directed onto a retinal surface of an eye thereby to permit measurement of refractive characteristics of the eye.

 7. Apparatus as claimed in claim 4 wherein the beam is a Nd:Yag laser beam.

10 8. Apparatus as claimed in claim 4 wherein the beam has a wavelength in the range of about 400 to about 500 nanometers, and wherein the beam is directed onto an epithelial surface of a cornea of an eye.

15 9. Apparatus as claimed in claim 8 wherein the wavelength is about 470 nanometers.

 10. Apparatus as claimed in claim 8 wherein the beam is an Argon Ion laser beam.

20 11. Apparatus as claimed in claim 4 wherein the wavelength of the beam is in the range of about 500 to about 550 nanometers and is directed to an endothelial surface of a cornea of an eye.

25 12. Apparatus as claimed in claim 11 wherein the wavelength is about 525 nanometers.

30 13. Apparatus as claimed in claim 11 wherein the beam is an Argon Ion laser beam.

35 14. Apparatus as claimed in claim 1 wherein different beams are selectively directed at different surfaces of selected elements and wherein a first beam is directed at an epithelial surface of a cornea and a

second beam is directed at an endothelial surface of a cornea and wherein the analysis means provides data of the epithelial surface, and data of the endothelial surface, and a measurement of the thickness of the cornea over a predetermined corneal area.

15. Apparatus as claimed in claim 14 wherein a third beam is directed at a retinal surface thereby to provide data relating to the refractive characteristics of the retinal surface, the beam being directed over a predetermined area of the retinal surface.

16. Apparatus as claimed in claim 15 wherein the means for analyzing the moire pattern selectively analyzes data from the beam directed the retinal surface, the beam directed at the epithelial surface and the beam directed at the endothelial surface, the analyzing means thereby providing informational characteristics of the refractive characteristic of an eye as determined by the reflection from the retinal surface, and the reflection characteristics of the eye as effected by the cornea over a predetermined area of the cornea.

17. Apparatus as claimed in claim 16 including means for analyzing the refractive information to provide data for changing the refractive characteristics.

18. Apparatus as claimed in claim 14 wherein the epithelial information is analyzed to provide data about the shape of the cornea.

19. Apparatus as claimed in claim 14 including means for analyzing the epithelial information and endothelial information for providing data about the corneal thickness.

20. Apparatus as claimed in claim 1 wherein the beam is directed at an element surface which is irregular.

5 21. Apparatus as claimed in claim 1 wherein the element includes a surface which is essentially curvilinear.

10 22. Apparatus as claimed in claim 1 wherein the surface is essentially circular.

15 23. Apparatus as claimed in claim 1 wherein the beam is directed at elements having multiple surfaces substantially simultaneously, and including multiple analyzing means for determining multiple characteristics of the elements.

20 24. Apparatus as claimed in claim 23 wherein the beam is directed to a second surface and wherein a reflection from the first surface and a second surface is processed by respective analyzing means, and wherein the surfaces are related such that the analyzing means can provide information from both the surfaces thereby to provide interrelated data of both surfaces.

25 25. Apparatus as claimed in claim 1 including means for storing data representative of the element parameters.

30 26. Apparatus as claimed in claim 1 wherein the analyzing means includes means for tracking relative movement of the element.

27. Apparatus as claimed in claim 26 including means to determine movement in any one of three dimensions.

5 28. Apparatus as claimed in claim 1 including directing a beam at a predetermined wavelength towards a lens surface of an eye, the wavelength being selected to be reflected from at least one of the interfaces of the lens with its surroundings in the eye.

10 29. Apparatus as claimed in claim 1 including means for continuously measuring the wavefront of the beam as projected in the pattern thereby to continuously obtain measurement parameters of the surface.

15 30. Apparatus as claimed in claim 1 wherein the surface is selectively animate or inanimate.

20 31. Apparatus for processing a fringe pattern, the pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

25 (b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern; and

(c) means for demodulating the signal information of the fringe pattern thereby to obtain measurement characteristics represented by the fringe pattern.

30 32. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

35

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

5 (b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern;

10 (c) means for receiving the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide a scaled fringe pattern; and

15 (d) means for demodulating the scaled signal information of the fringe pattern for obtaining the measurement characteristic represented by the fringe pattern.

20 33. Apparatus as claimed in either claim 31 or claim 32 including means for processing the demodulated signal information thereby to determine wavefront data representative of the measurement characteristics.

25 34. Apparatus as claimed in claim 33 wherein the measurement characteristics represent three dimensional topographic information.

30 35. Apparatus as claimed in claim 33 including means for receiving multiple representations of the demodulated signal information and including means for averaging the multiple representations thereby to obtain an output signal representative of measurement characteristics.

36. Apparatus as claimed in claim 35 including means for analyzing and presenting the measurement characteristics.

5 37. Apparatus as claimed in either claim 31 or claim 32 wherein the input fringe pattern is image data representative of an anatomical surface.

10 38. Apparatus as claimed in claim 32 wherein the image data is selectively representative of at least one of the retinal surface, epithelial surface or endothelial surface of the eye.

15 39. Apparatus as claimed in either claim 31 or claim 32 wherein the input fringe pattern is a interferometric pattern.

20 40. Apparatus as claimed in claim 39 wherein the input fringe pattern is a moire pattern.

41. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

5 (a) means for receiving data representative of an input fringe pattern;

(b) means for demodulating the data to obtain information representative of a measurement characteristic;

0 (c) means for obtaining further representations of the demodulated data and for averaging the data to obtain an effective average as an output signal representative of the measurement characteristics;

(d) means for removing anomalies falling significantly beyond the effective average; and

(e) means for analyzing the output signal and presenting the output signal as a representation of the measurement characteristics.

5 42. Apparatus as claimed in claim 41 wherein the input data is selectively representative of at least one of the surface characteristics of the eye, the surface being selectively the retinal surface, endothelial surface or the epithelial surface.

10 43. Apparatus as claimed in either claim 31 or claim 32 wherein the demodulation means effectively converts the data into a sinusoidal wave pattern, the sinusoidal wave pattern having phase modulated and
15 frequency modulated characteristics, and wherein the phase modulated characteristics is representative of depth in a topographical sense and the frequency modulated signal is representative of the slope of a surface.

20 44. Apparatus as claimed in either claim 31 or claim 32 wherein the demodulation means effectively treats a fringe pattern as a continuing communication signal, the communication signal being analyzed by the demodulation means.

25 45. Apparatus as claimed in either claim 31 or claim 32 wherein the filtering means includes means for selectively analyzing discrete portions of the fringe pattern for determining local noise and background in the
30 discrete portions.

35 46. Apparatus as claimed in claim 32 wherein the means for scaling provides a scaled fringe pattern, the scaling means selectively normalizing discrete portions of the fringe pattern.

47. Apparatus as claimed in claim 46 including means for comparing the data before scaling with the data after scaling thereby to obtain information about surface roughness being represented by the measurement characteristics.

48. Apparatus for electronically processing a fringe pattern to obtain measurement characteristics, the fringe pattern being representative of the measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise; and

(b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern, wherein the filtering means includes a Fourier transform based local area filter.

49. Apparatus as claimed in claim 48 wherein the filtering means includes a Fourier transform based local area filter.

50. Apparatus as claimed in claim 49 wherein the receiving data is directed to Fourier transform means, the output of the Fourier transform means being directed firstly to means for estimating the signal spectrum, and secondly to means for estimating the input power spectrum, and means for receiving the first and second spectrum estimations, the receiving means being computation means for a filter transfer function, the output of the computation means being directed to means for complex multiplying the function with the transformed receiving data, and means for receiving the complex multiplied signal and performing an inverse Fourier

transform thereby to provide an output signal representative of the fringe pattern with noise removed.

5 51. Apparatus as claimed in claim 50 wherein the means for signal spectrum estimation provides an estimate of a center frequency and an estimate of the spectral content of the signal, such estimates being an indication of the signal information without noise.

10 52. Apparatus as claimed in claim 50 wherein the input power spectrum estimation means provides an estimate of the signal information and noise of the entire input signal.

15 53. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

20 (a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) filtering means for removing the noise information thereby to provide the signal information representative of the fringe pattern; and

25 (c) means for scaling the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide scaled signal information representative of the fringe pattern, and wherein the scaling means
30 is an adaptive surface roughness compensation means.

35 54. Apparatus as claimed in claim 53 wherein the compensation means includes means for dividing the fringe pattern into discreet pixels, means for defining a neighborhood about each pixel, means for collecting data

within the neighborhood, means for computing a minimum and a maximum contrast signal within the neighborhood, and means for scaling the minimum and maximum signal thereby to provide a scaled value of the pixel within the neighborhood.

55. Apparatus as claimed in claim 54 wherein the size of the neighborhood is selected to contain at least one fringe maximum and one fringe minimum signal.

56. Apparatus as claimed in claim 54 wherein the fringe pattern is represented by a moire pattern, and the maximum signal is represented by a dark line of the moire pattern and the minimum signal by a space between the dark lines in the moire pattern, and wherein scaling effectively adjusts each pixel to vary between a maximum and a minimum, the maximum and the minimum being applicable to adjacent pixels.

57. Apparatus for delivering laser energy to a target in a cornea region of an eye comprising:

(a) means for generating energy in a laser beam at a predetermined wavelength such that energy is absorbed by water;

(b) means for focusing the energy to a selected part in the cornea at a predetermined selected depth between an epithelial surface of the cornea and an endothelial surface of the cornea whereby the energy in the laser beam heats the target; and

(c) means for tracing the laser beam on a selected path and heating the cornea at selected targets on that path thereby to change the shape of the cornea.

58. Apparatus as claimed in claim 57 wherein the target is in a stroma region of the cornea.

59. Apparatus as claimed in claim 57 wherein the traced path forms a closed loop.

5 60. Apparatus as claimed in claim 59 wherein the closed path forms a Schwalbe's-like line.

10 61. Apparatus as claimed in claim 57 wherein the intensity at the target is in the range of between about 0.5 to about 2 watts/cm².

62. Apparatus as claimed in claim 61 wherein the intensity is in the range of about 1.1 watts/cm².

15 63. Apparatus as claimed in claim 57 wherein the beam focuses energy at the target to form a diameter of between about 10 to about 50 microns.

64. Apparatus as claimed in claim 63 wherein the focus diameter is about 25 microns.

20 65. Apparatus as claimed in claim 57 wherein the intensity of the beam at the epithelial surface is about 5×10^{-3} watts/cm².

25 66. Apparatus as claimed in claim 57 wherein the intensity at the endothelial is about 2.0×10^{-4} watts/cm².

30 67. Apparatus as claimed in claim 57 wherein the laser beam is generated by a CO₂ laser.

35 68. Apparatus as claimed in claim 57 wherein the laser beam is focused towards the target at a + number of about 0.76.

69. Apparatus as claimed in claim 59 wherein the traced path is a regular curve.

5 70. Apparatus as claimed in claim 69 wherein the curve is selectively a circle or an ellipse.

71. Apparatus as claimed in claim 59 wherein the traced path is an irregular curvilinear shape.

10 72. Apparatus as claimed in claim 57 including means for measuring the refractive characteristics of the eye, means for feeding data representative of the refrac-
15 tive characteristics to the means for tracing the laser beam on the selected path, and means for causing the tracing means to follow a path to provide different
20 refractive characteristics of the eye by changing the shape of the cornea in terms of the traced path and thereby to effect a change of the refractive character-
istics.

25 73. Apparatus as claimed in claim 57 including means for directing a patient to view a three dimensional image through a stereoscope, means for measuring the refractive characteristics of the eyes of a patient,
30 means for measuring the shape and thickness of the cornea of the eyes and means for determining the refractive changes necessary to change the overall refraction of the eyes, and means for delivering the laser beam to the target on a selected path to thereby change the refrac-
tion characteristics of the eyes.

35 74. Apparatus as claimed in claim 72 including computer control means for coordinating the measuring and changing characteristics.

75. Apparatus as claimed in claim 74 including feedback means for continually controlling the laser beam operation and tracing means.

5 76. Apparatus as claimed in claim 57 including directing the energy to water molecules in a stroma of the eye.

10 77. Apparatus as claimed in claim 57 wherein means is provided for analytically dividing the corneal region into finite elemental areas, computing means for analyzing relative stress factors between the finite elemental areas, means for determining the heating effect on one or more selected finite elemental areas relative to stress factors between the elemental areas thereby to change the physical relationship between the respective elemental areas and the physical corneal material, and means for directing the application of heat to selected elemental areas.

20 78. Apparatus as claimed in claim 57 including means for optically analyzing the corneal region in elemental areas, and means for applying a structural analysis technique to the elemental areas to provide information about the effect of applying heat to the elemental areas.

30 79. Apparatus as claimed in claim 78 including means for applying energy to selected elemental areas as determined by the finite elemental analysis thereby to change the optical refractive system in the eye.

35 80. Apparatus as claimed in claim 77 wherein the selected elemental areas are the target of the beam.

81. Apparatus as claimed in claim 79 wherein the selected elemental areas are the target of the beam.

5 82. Apparatus as claimed in claim 73 including means for changing substantially simultaneously the refractive characteristics of two eyes of a patient.

10 83. Apparatus as claimed in claim 73 including means for selectively viewing images at different depths at different predetermined times, means for obtaining refractive information at the respective predetermined times, means for determining data for changing the refractive characteristics, and means for delivering a laser beam to heat the cornea and thereby change the refractive characteristics according to the determined data.

15 84. A method for measuring a predetermined parameter of an element comprising:

- 20 (a) generating a collimated light beam;
(b) directing the beam onto the element wherein the beam is reflected from the element;
(c) directing the reflected beam through a first grating to develop a wavefront;
5 (d) directing the wavefront through a second grating to develop a moire pattern; and
(e) analyzing the moire pattern to produce measurement data of the element.

85. A method as claimed in claim 84 including converging the beam being related to provide a beam front substantially parallel to the surface of the element.

86. A method as claimed in claim 84 including removal of noise and determining a substantially noise-

free moire pattern thereby to provide measurement data of the element.

87. A method for processing a fringe pattern, the pattern being representative of measurement characteristics, comprising:

(a) receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) removing the noise thereby to provide the signal information representative of the fringe pattern; and

(c) demodulating the signal information of the fringe pattern thereby to obtain measurement characteristics represented by the fringe pattern.

88. A method for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

(a) receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) removing the noise thereby to provide the signal information representative of the fringe pattern;

(c) receiving the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide a scaled fringe pattern; and

(d) demodulating the scaled signal information of the fringe pattern for obtaining the measurement characteristic represented by the fringe pattern.

89. A method for delivering laser energy to a target in a cornea region of an eye comprising:

(a) generating energy in a laser beam at a predetermined wavelength such that energy is absorbed by water;

(b) focusing the energy to a selected part in the cornea at a predetermined selected depth between an epithelial surface of the cornea and an endothelial surface of the cornea whereby the energy in the laser beam heats the target; and

(c) tracing the laser beam on a selected path and heating the cornea at selected targets on that path thereby to change the shape of the cornea.

Page 1 of 9

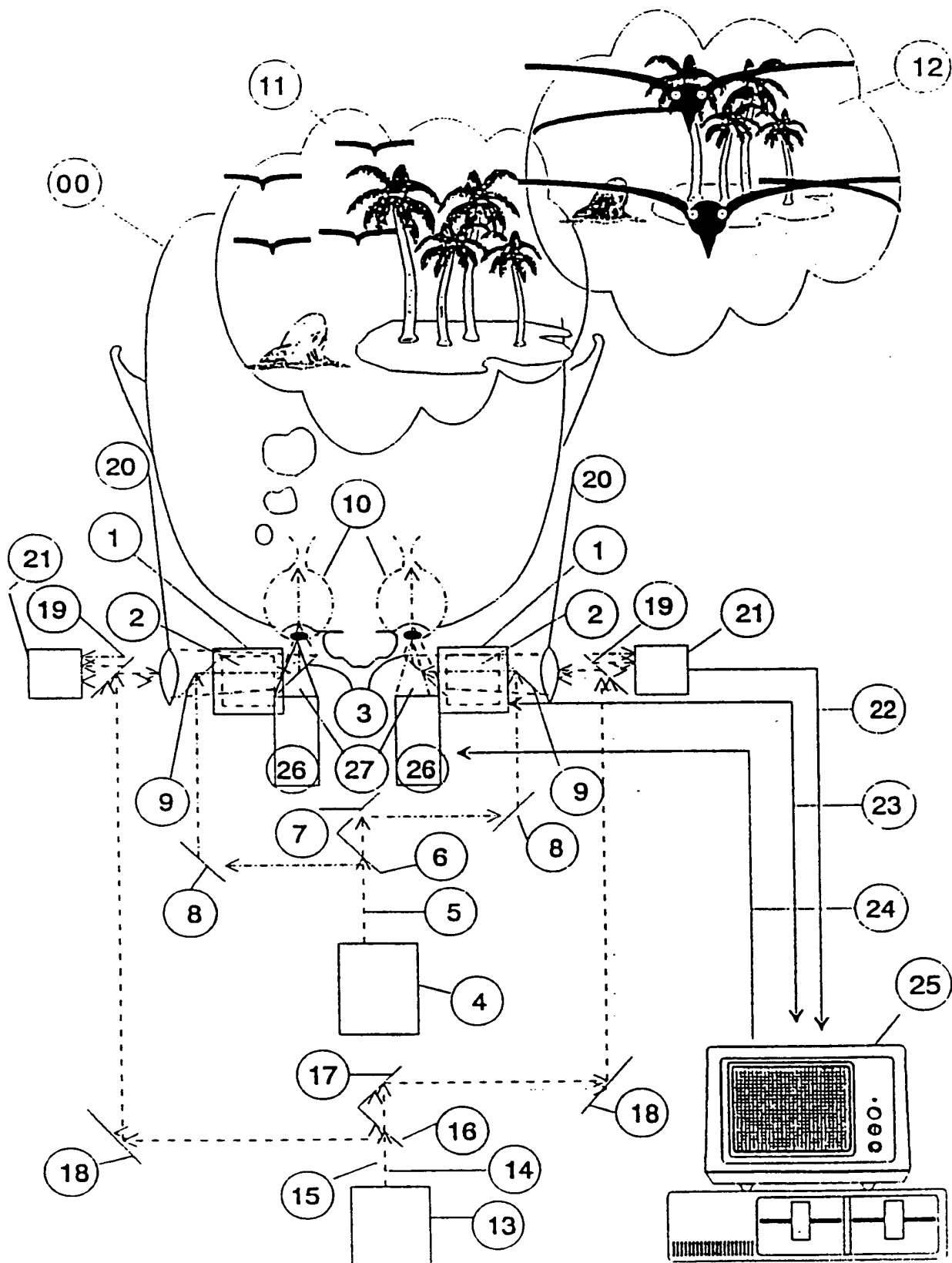


Figure 1

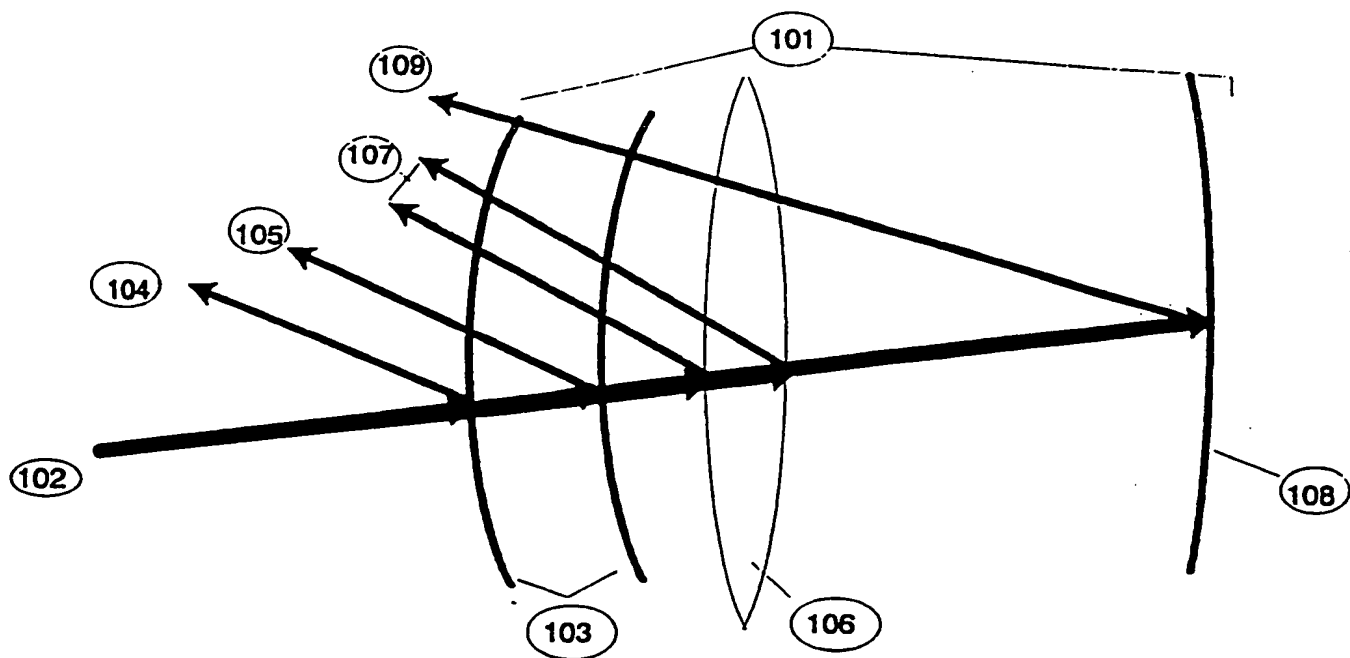


FIGURE 2

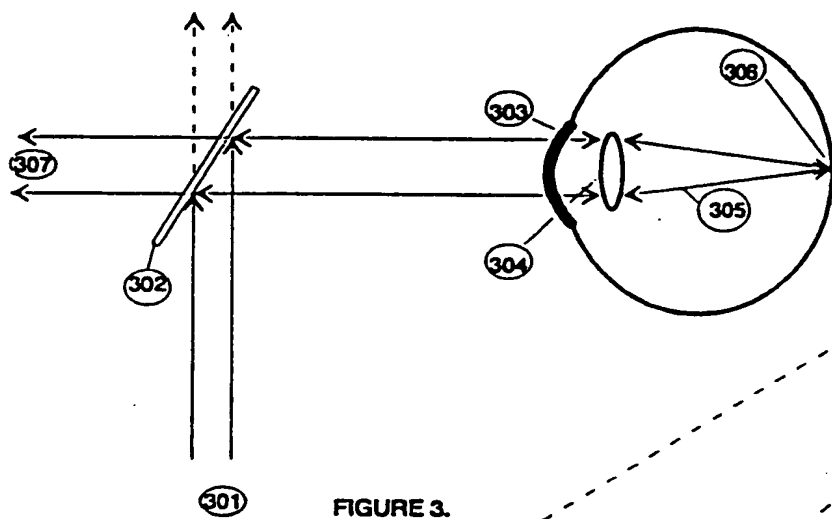


FIGURE 3.

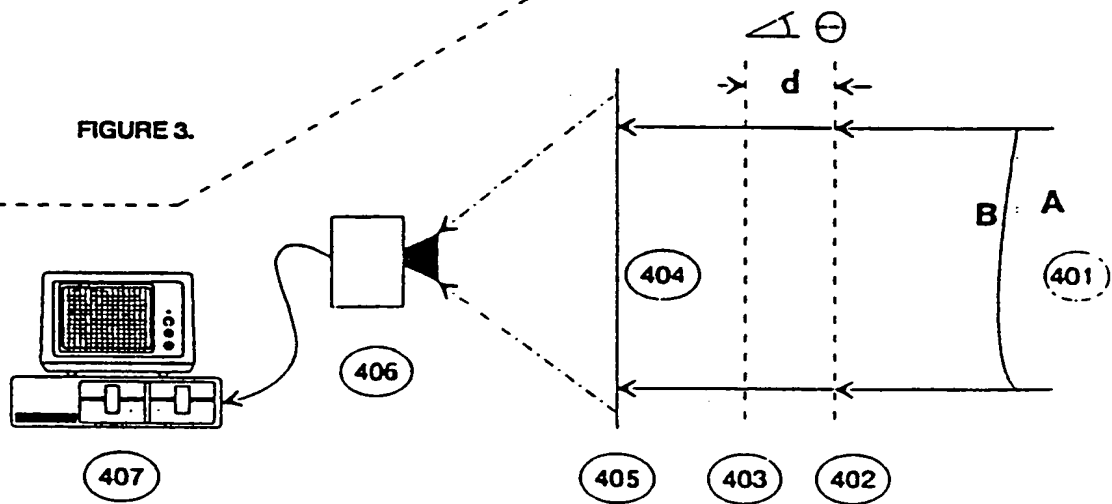


Figure 4

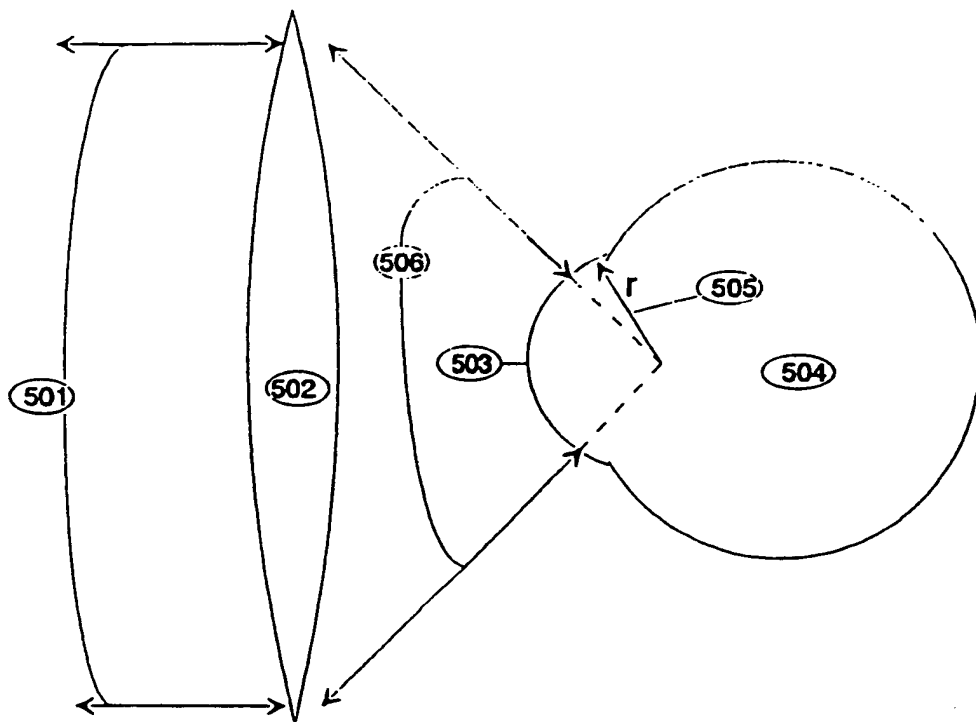


Figure 5

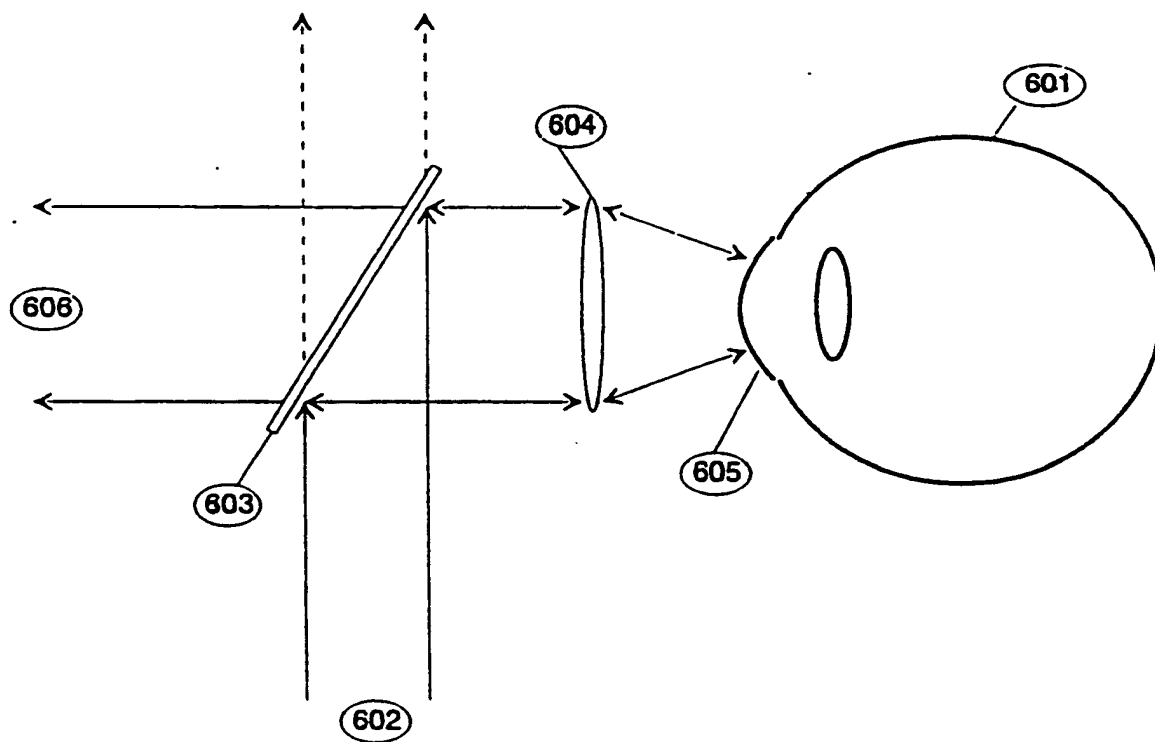


Figure 6

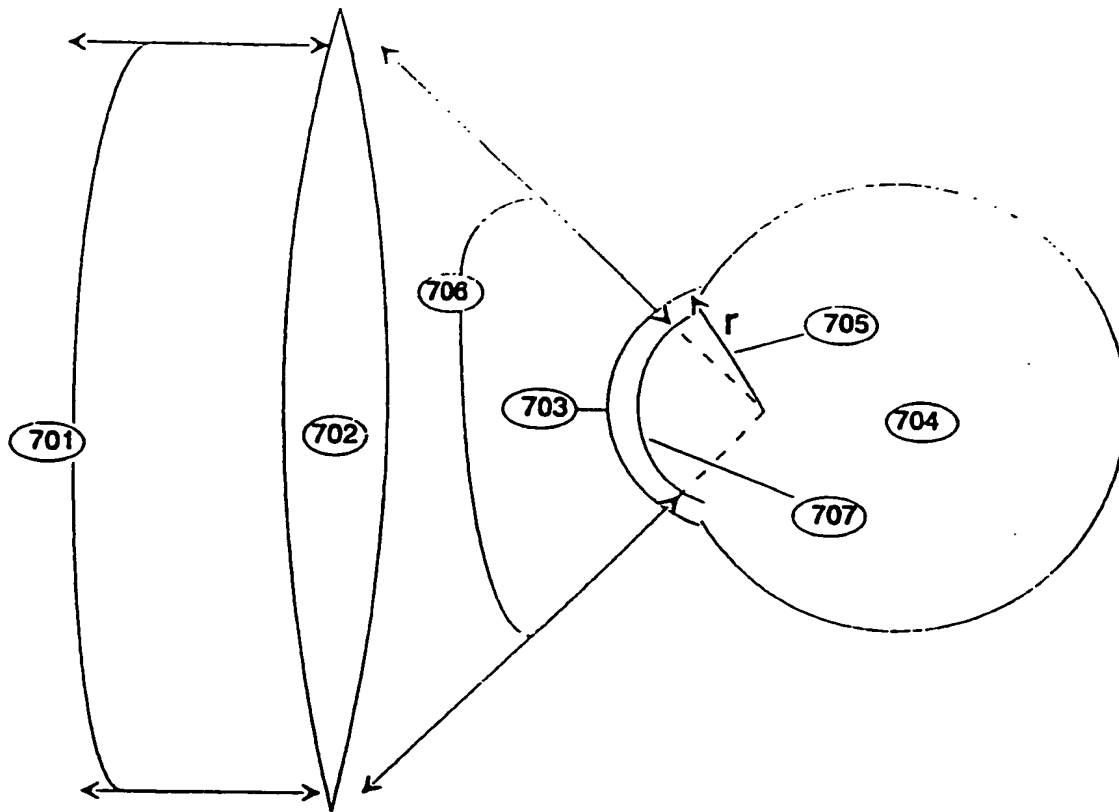


Figure 7

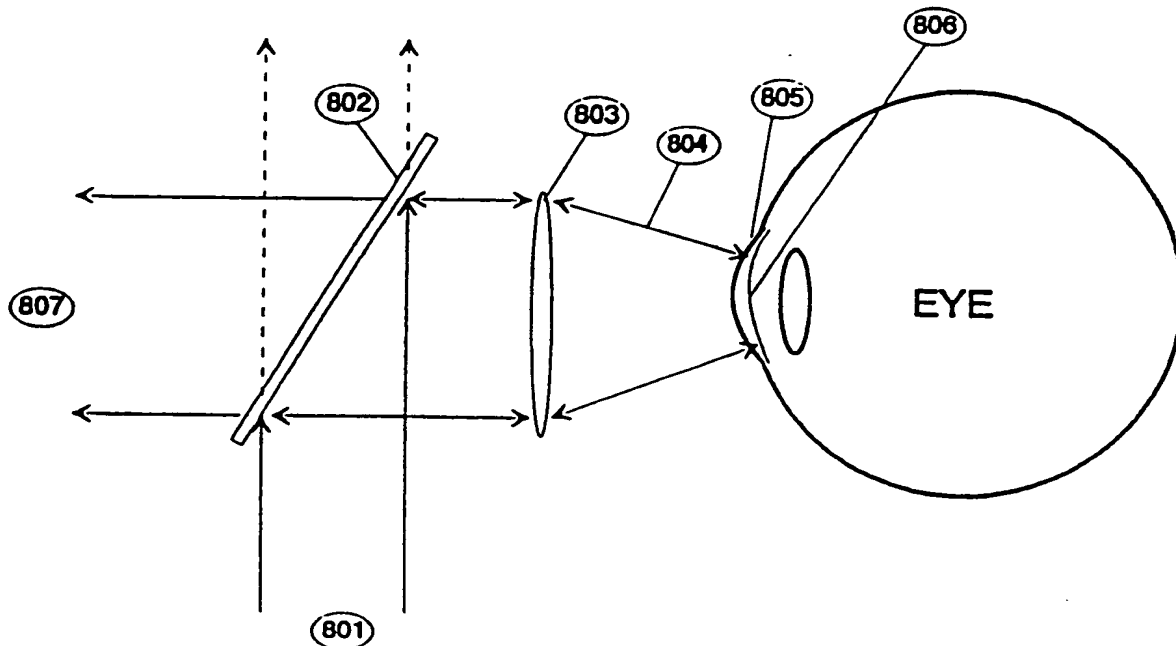


Figure 8

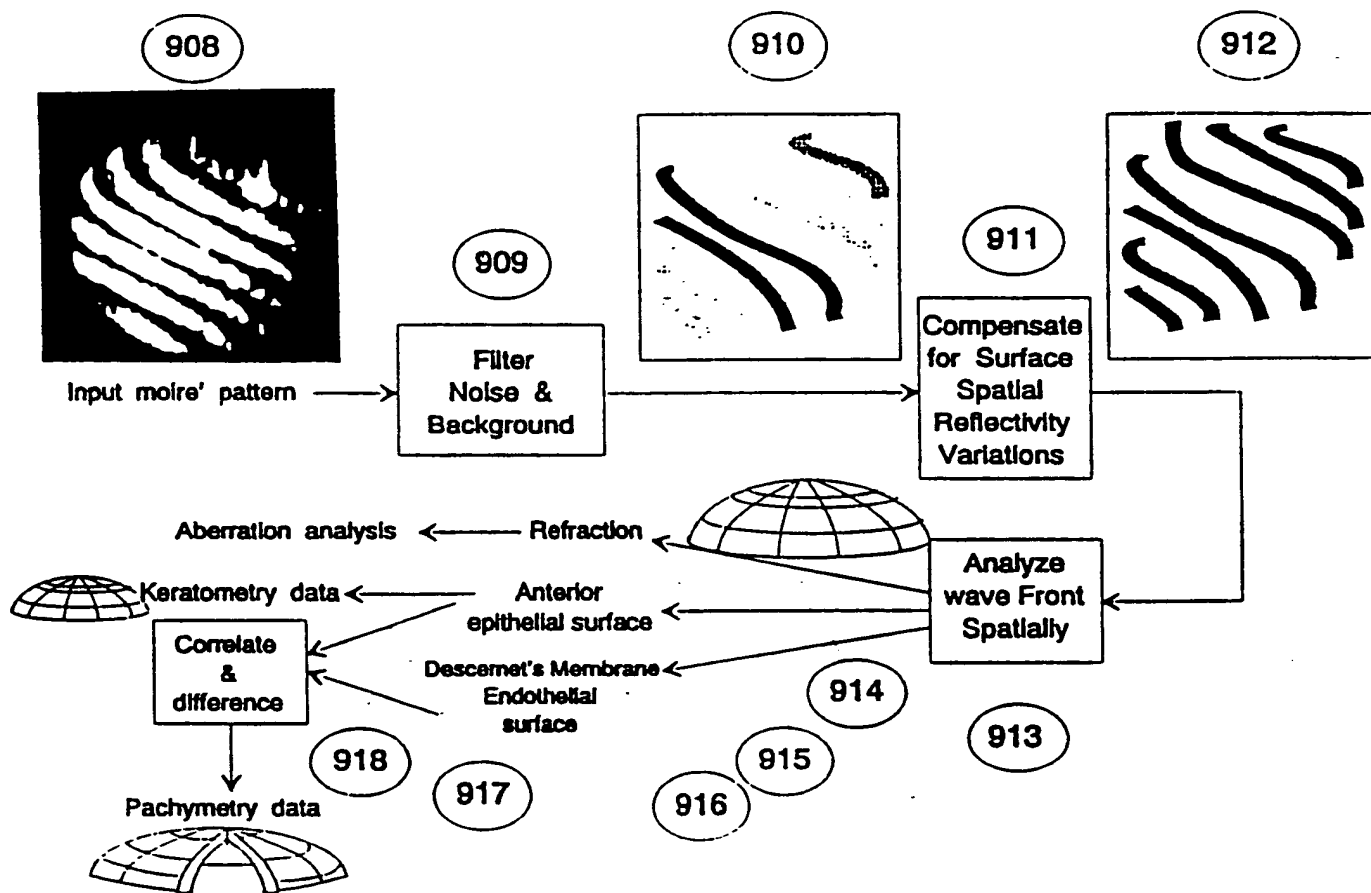


Figure 9

BEST AVAILABLE COPY

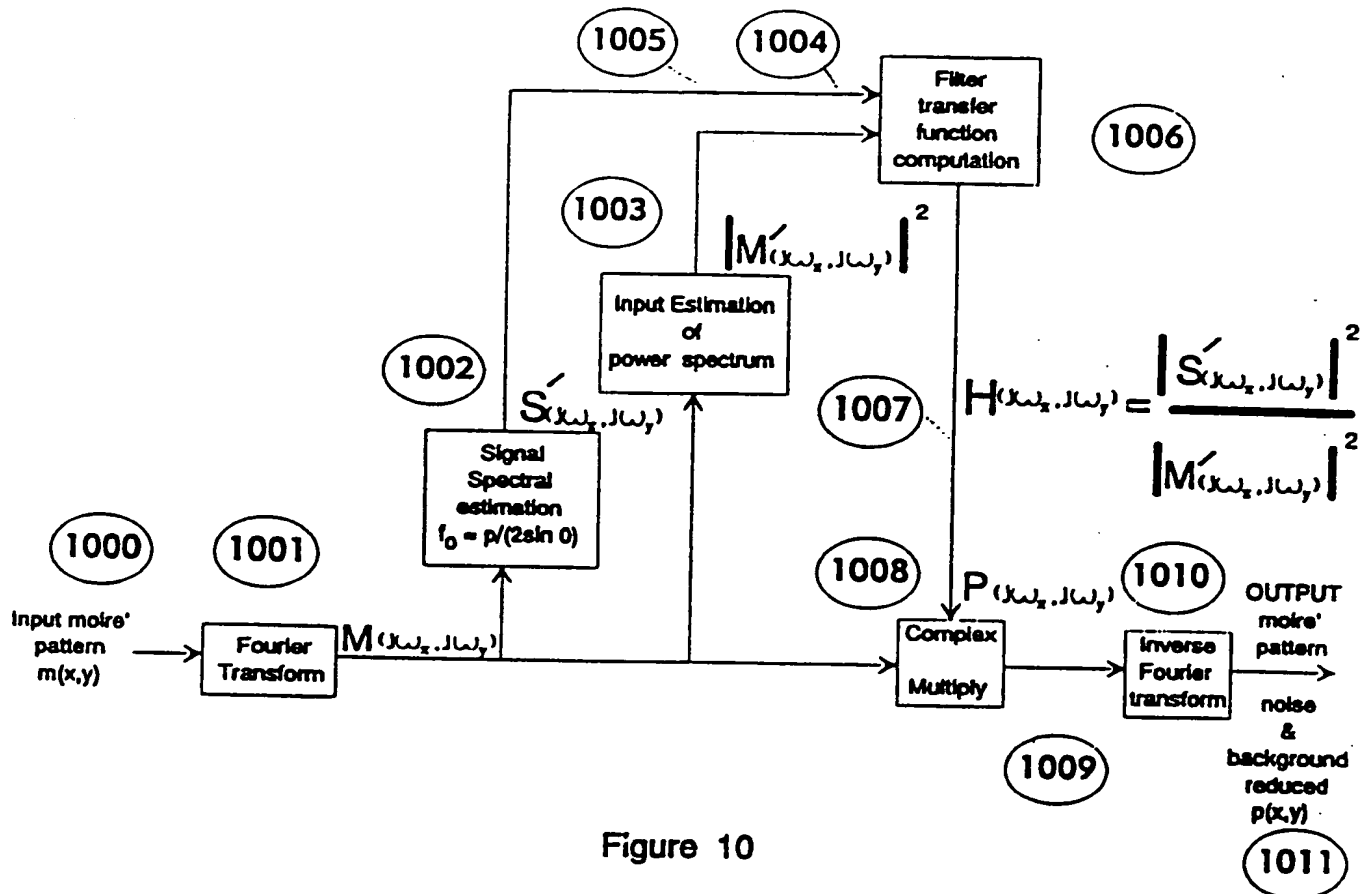


Figure 10

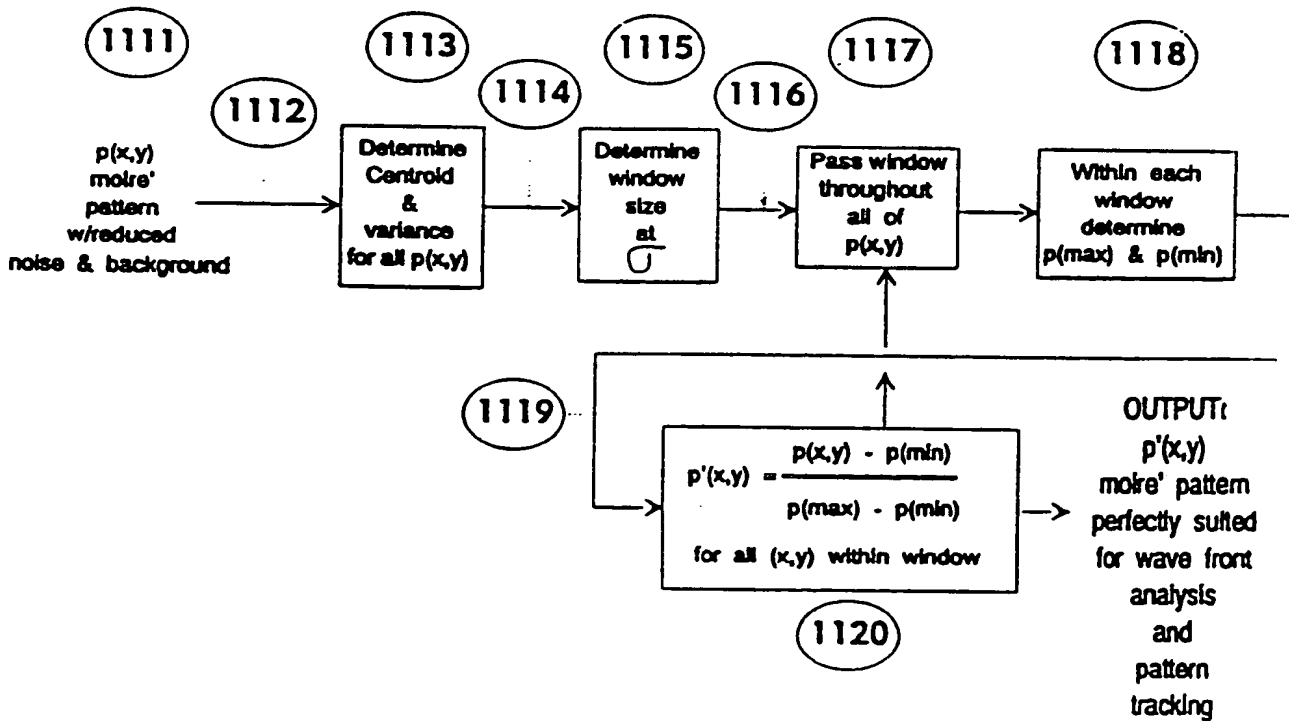


Figure 11

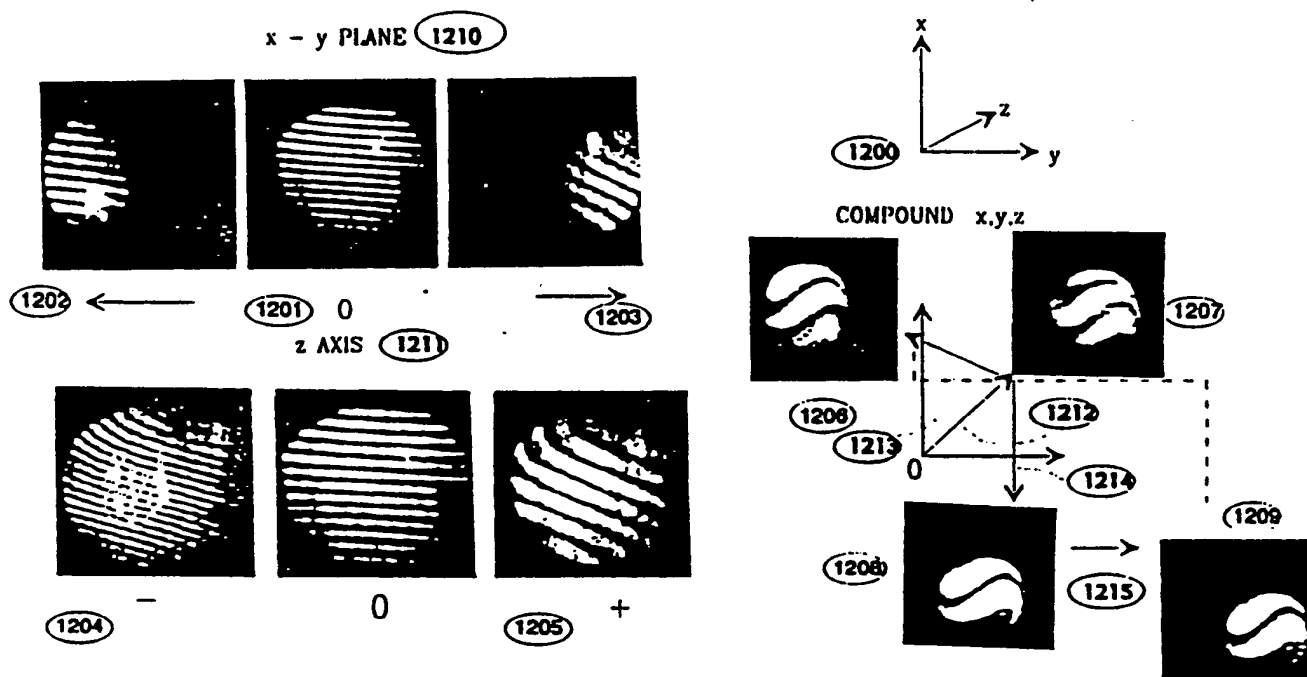


Figure 12

BEST AVAILABLE COPY

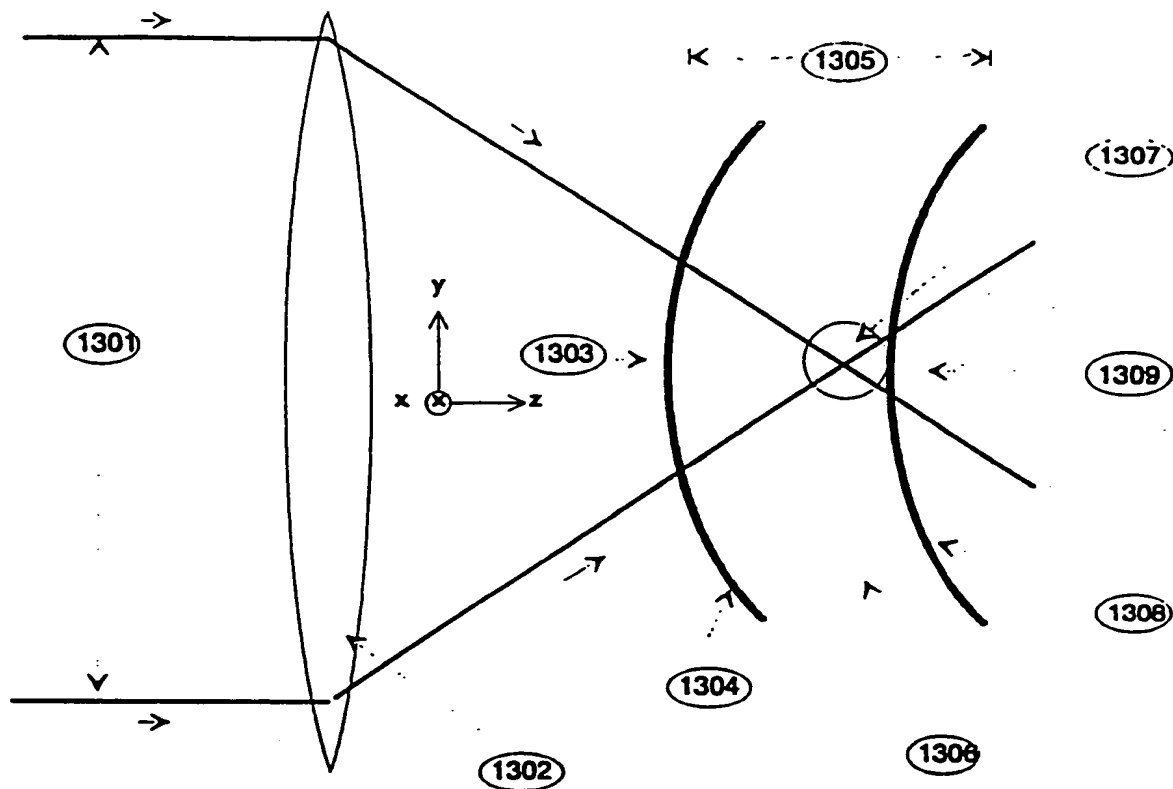


Figure 13

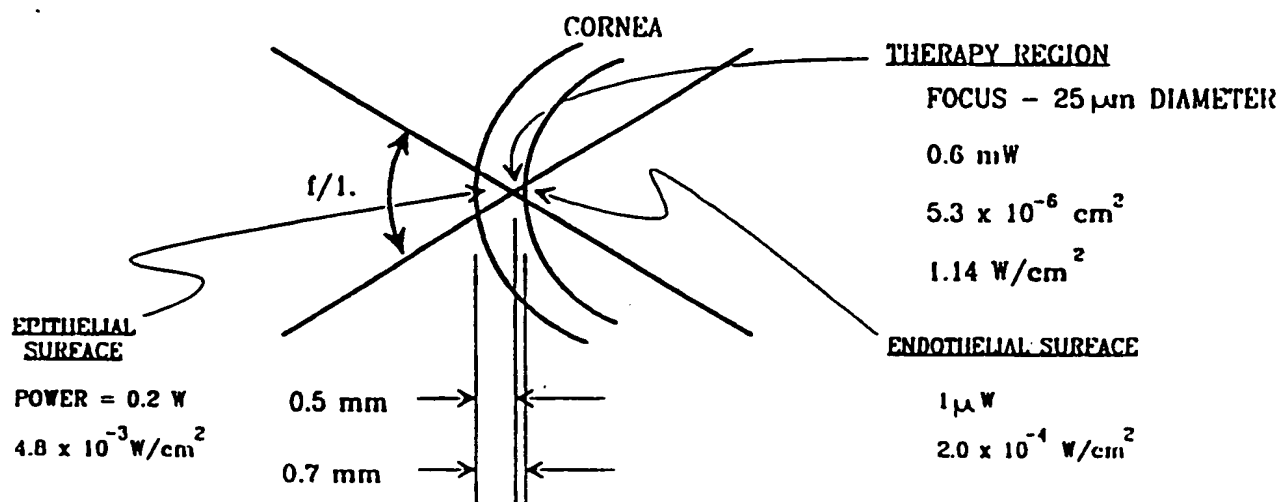


Figure 14

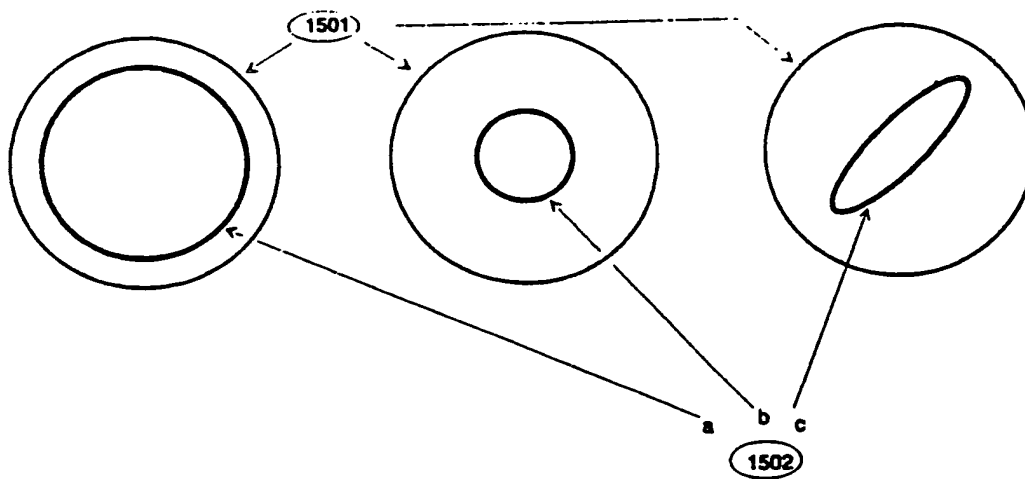


FIGURE 15

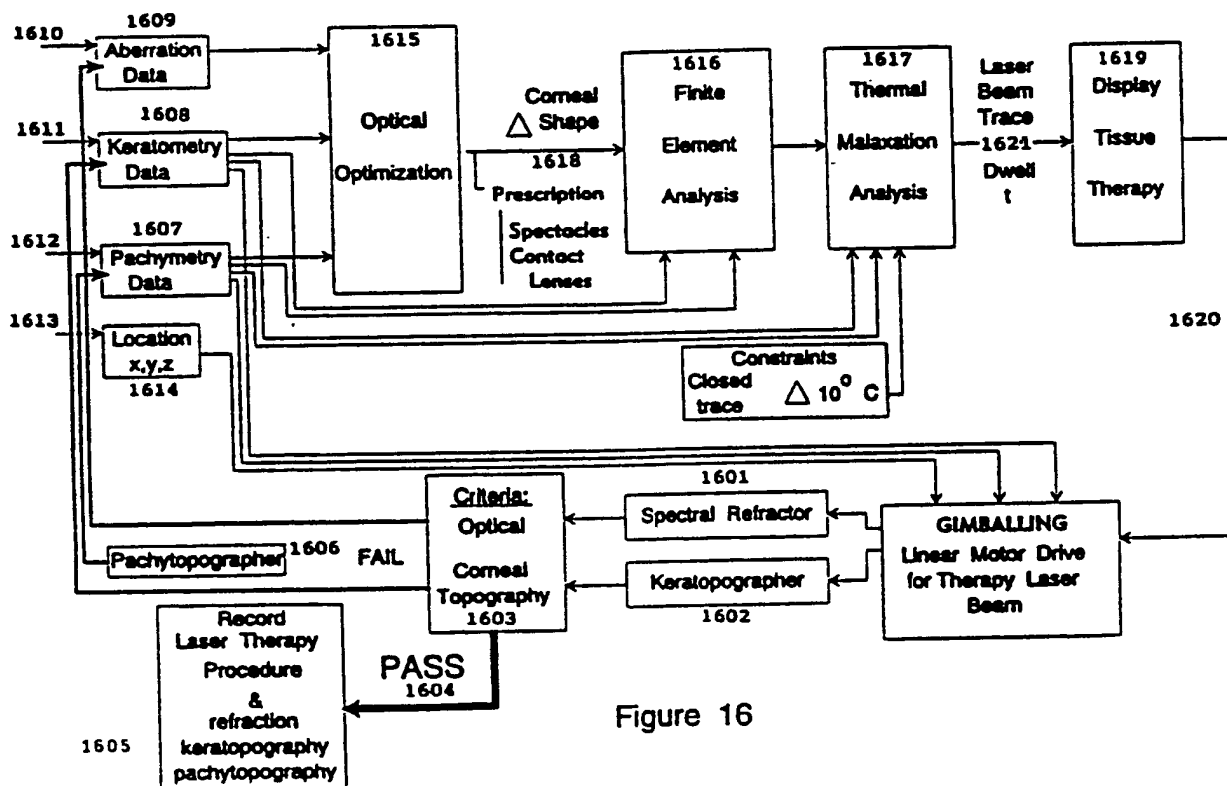


Figure 16

INTERNATIONAL SEARCH REPORT

International Application No. **PCT/US91/04976**

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) *

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5): **A61B 3/10**

U.S. CL.: **351/212,221**

II. FIELDS SEARCHED

Minimum Documentation Searched ⁷

Classification System

Classification Symbols

U.S.

351/212,205,221 128/395

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched *

III. DOCUMENTS CONSIDERED TO BE RELEVANT *

Category *	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
X	US,A, 4,692,003 (ADACHI et al.) 08 SEPTEMBER 1987 See entire document	1-30,84-86
X	US,A, 4,721,379 (L'ESPERANCE) 26 JANUARY 1988 See especially cols. 5-7	57-83,89
A	US,A, 4,964,715 (RICHARDS) 23 OCTOBER 1990 See cols. 2,3	57-83,89
A	US,A, 4,984,883 (WINOCUR) 15 JANUARY 1991 See cols. 3-5	1-30,84-86

* Special categories of cited documents: ¹⁰

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search

Date of Mailing of this International Search Report

22 NOVEMBER 1991

04 DEC 1991

International Searching Authority

Signature of Authorized Officer

ISA/US

PAUL M. DZIERZYNSKI

THIS PAGE BLANK (USPTO)